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AN EXPERIMENTAL ANALYSIS OF AN OBSERVING-RESPONSE IN RATS EXPOSED TO 1.28 AND 5.62 GHz MICROWAVE IRRADIATION

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November 1979

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Naval Medical Research and Development Command
MF58.524.015-0037

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SUMMARY PAGE

THE PROBLEM

Naval communications and weapons systems use a variety of microwave producing devices. Frequently fleet personnel may be exposed to the radio-frequency radiation emanating from such devices. Current scientific reports indicate that biological changes can be produced by nonionizing electromagnetic radiation and that complex behavioral effects are predominant among these changes.

Few studies of the biological effects of microwave radiation have investigated complex behavior in non-human organisms. One human behavior easily simulated in other animals is monitoring performance, otherwise known as observing-behavior or performance on a vigilance task. This task requires an animal to respond, thereby producing one or more stimuli. When the stimuli change, the animal has to report the change to obtain a reinforcer. In the present study the effects of two different microwave frequencies (1.28 and 5.62 GHz) on observing-behavior in rats were investigated.

FINDINGS

At 1.28 GHz the observing-response rate was consistently affected at an exposure power density of 15 mW/cm^2 in all eight rats while at 5.62 GHz the observing-response rate was not consistently affected until the power density approximated 26 mW/cm^2. Measurements of the localized specific absorption rate (SAR) in a rat-shaped model of simulated muscle tissue revealed differences in the absorption pattern for the two frequencies. The SAR within the model's head at 1.28 GHz was higher on the side opposite the irradiation source. The SAR distribution was exactly opposite at 5.62 GHz. It was concluded that the rat's behavior was more easily disrupted at 1.28 GHz than at 5.62 GHz because of the deeper penetration of energy at 1.28 GHz and the differences in energy distribution at the two frequencies.

ACKNOWLEDGMENTS

Dr. R. G. Olsen's assistance in various phases of this study is greatly appreciated as is the assistance of T. Griner and D. Prettyman. We also wish to thank D. Early for her assistance in preparation of this report.

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The animals used in this study were handled in accordance with the Principles of Laboratory Animal Care established by the Committee on the Guide for Laboratory Animal Resources, National Academy of Sciences-National Research Council.

INTRODUCTION

This report is concerned with the investigation of behavioral effects of microwaves produced by radar sources representative of those currently used in the Navy. The investigation was prompted partially by the extreme difference between safety standards for microwave radiation exposure in the Soviet Union and in the United States (15), and partially by the sparsity of definitive, parametric experiments on behavioral effects of such exposure.

Our contribution to the resolution of these problems has been a series of studies defining the relationship between the body mass of a mammal and the microwave power density necessary to disrupt behavior on a complex operant task analogous to tasks engaged in by humans. It is possible that analogues of human behavior may be very susceptible to microwave radiation. One such parallel is observing-behavior or performance on a vigilance task. In experiments on human vigilance, subjects are presented aperiodically with superthreshold stimuli to which they are instructed to respond differentially (13). The stimuli are called "signals" and responses to them are called "detections." Holland (8) developed a technique for controlling human vigilance by having the subject illuminate a meter dial before reporting whether the needle on the dial was offset (detection). The response, a depression of a telegraph key which illuminated the meter dial, was called the "observing-response." Holland's experiments showed that detections functioned as reinforcement for observing-responses, and that observing-behavior was controlled by events similar to the controlling events of "vigilance" behavior in its traditional meaning. The empirical content of the question whether an observing-response represents "true vigilance" is largely a matter of whether neural events affecting discrimination are controlled by reinforcement or other variables in the same manner as overt observing-responses.

The experiments reported here were designed to produce observing- and detecting-behavior in rats under a schedule similar to those typically employed in human monitoring experiments. Signals occurred aperiodically if the rat continually monitored the stimuli, and a detection response in the presence of the transient signals resulted in delivery of a food pellet. The vigilance task herein reported is described in operant conditioning terminology as a heterogenous chained schedule of reinforcement, Chain VI 20-sec, FR 1 with a limited hold of 10 sec (2).

Previous experiments (4, 5, 14) in this series of studies have provided sufficient data on the rat, squirrel monkey, and rhesus monkey to construct a preliminary scale based on body mass and behavioral changes at one microwave frequency, 2.45 GHz. The purpose of the present experiments was to discover the power density at which rats working a vigilance task would have their behavior disrupted when exposed to two other frequencies, 1.28 and 5.62 GHz.

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PROCEDURE

SUBJECTS

Eight male rats of the Long Evans strain obtained from the Charles River colonies served as subjects. The mean body mass of the food-deprived rats during the 5.62 GHz exposure phase (the initial phase) of the study was 362 ± 16 g. During the 1.28 GHz exposure phase it was 400 ±18 g. These maintenance levels were 90 and 88 percent of their free-feeding body mass during the 5.62 GHz and 1.28 GHz exposures, respectively. Water was continuously available in the home cages.

APPARATUS

Two microwave anechoic exposure chambers, one for 1.28 GHz and one for 5.62 GHz, were used. The exterior dimensions of the lower-frequency chamber were 3.40 m long x 2.20 m wide x 2.35 m high. The exterior dimensions of the higher-frequency chamber were 2.54 m long x 1.94 m wide x 2.43 m high. The chamber interiors were shielded with copper and lined with 20-cm pyramidal absorber (AAP-8) obtained from Advanced Absorber Products, Amesbury, MA. Inside each chamber were two small audio-speakers, a closed-circuit TV camera, a 100 W incandescent lamp, a 25 W incandescent lamp, and a Styrofoam stand for holding the operant conditioning box. The 100 W lamp, TV camera, and speakers were located above and behind the microwave horn at a far end of each chamber. The chambers were ventilated at an air exchange rate greater than 28 m^3 per minute, and the operant conditioning box was placed in the center of the air flow. The 25 W lamp was centered 57 cm directly over the conditioning box and was illuminated at the start of and during a session. A schematic of the 1.28 GHz chamber is shown in Figure 1. The higher-frequency chamber is basically identical except for the differences in dimensions.

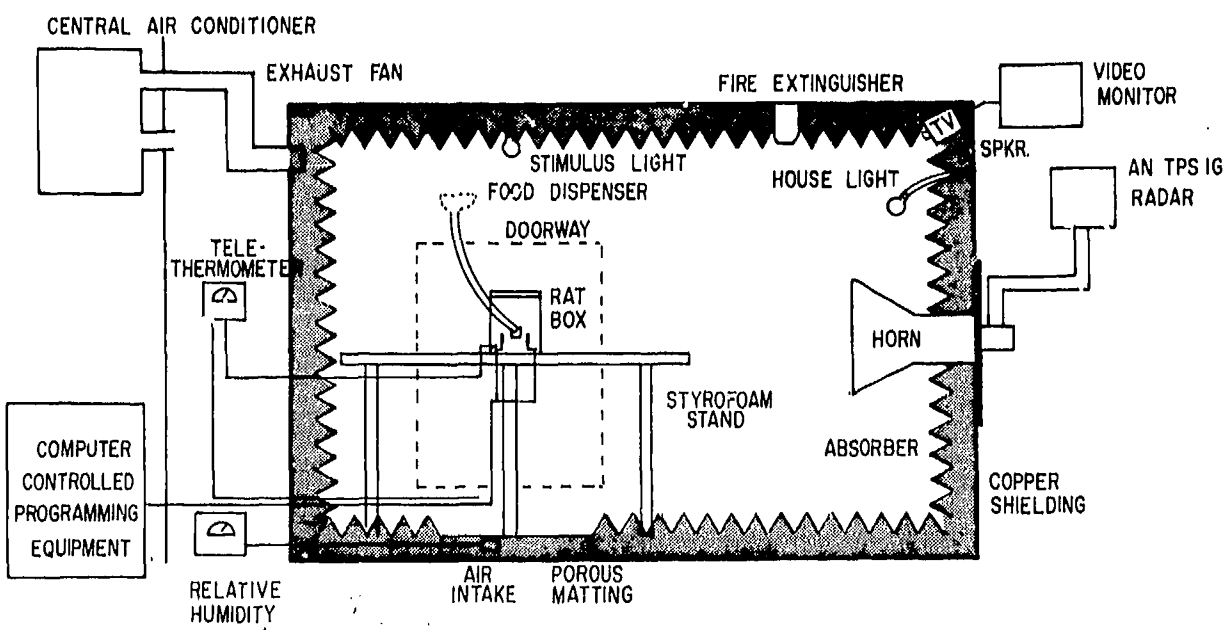

Figure 1. Diagram of the 1.28 GHz exposure chamber. The food dispenser was located outside of the chamber.

A AN/TPS-1G radar set (Hazeltine Corp., Little Neck, NY) provided the 1.28 GHz energy, pulsed at 370 pps with a pulse duration of 3 μs. A AN/SPS-4 radar set (Raytheon Manufacturing Co., Waltham, MA) provided the 5.62 GHz microwaves, pulsed at 662 pps with a pulse duration of either 0.5 or 2 μs. A custom-made horn was connected with a coaxial transmission line to the AN/TPS-1G radar, and a standard gain horn, Narda Model 643 (Narda Microwave Corp., Plainview, NY), was connected with waveguide to the AN/SPS-4. In each chamber the right side of the rat was irradiated while the animal was lever responding. Horizontal propagation was used with the E vector vertically polarized. According to Durney et al. (6), little difference in average energy deposition exists between E and H vectors for a rat exposed to 5.62 GHz irradiation. However, at 1.28 GHz a rat aligned with the E vector could absorb almost twice as much energy as the rat aligned with the H vector. It was unlikely that the rats in these experiments faced the horn because of the configuration of the operant conditioning box and the stringent work requirements.

Incident power density was measured in the absence of the rat with a Narda microline isotropic probe, model 8323, in three dimensions at 5-cm intervals through the center of the operant conditioning box. The power densities reported here refer to the region normally occupied by the rat while in the operant conditioning box. At 1.28 GHz power densities of 0 (sham), ≤1, 5.5, 9.5, 10, and 15 mW/cm^2 were used. At 5.62 GHz power densities of 0 (sham), 7.5, 11.5, 16, 26, 31.5, 38.5, 42, and 48.5 mW/cm^2 were used. All exposures occurred in the far-field region except for the 16 mW/cm^2 level at 5.62 GHz which was at 90 percent of the minimum far-field distance.

The operant conditioning box, shown in Figure 2, was constructed of 2.2 cm thick Styrofoam and was 30 cm deep x 25.5 cm long x 20 cm wide in the interior. The inner walls were coated with a quinine solution painted on a thin layer of epoxy. The quinine was to prevent gnawing by the rats and was not effective with two of the original group of ten animals. A nylon screen covered the top of the box and a polystyrene grid served as the floor. A Styrofoam waste tray was 5 cm below the grid floor. In the right-hand wall of the box (as seen from the horn) two Plexiglas levers 6 mm in diameter projected 5 mm into the interior of the box. Centered between the levers which were 13 cm apart was a polyvinyl food hopper, 1.5 cm in diameter, that projected 1.0 cm into the box. A plastic tube ran from the feeder outside the chamber to the hopper. The levers were 6 cm above the grid floor and the food hopper was 2.5 cm above the grid floor. Wires to the lever microswitches (located outside the box) were fed down the right side of the support stand and out of the anechoic chamber. A Yellow Springs Instruments' tele-thermometer, model 401 (Yellow Springs Instrument Co., Yellow Springs, OH), was oriented axially to the horn and located in the distal wall of the rat box below the floor. Local chamber temperature was recorded with this probe.

Temperature of the air in the chambers varied with building temperature between 23° C and 26.5° C with increases during the day. The local temperature increases during experimental sessions varied from 0.36° C to 1.68° C in the 5.62 GHz chamber and from 0.26° C to 1.20° C in the 1.28 GHz chamber. In the 1.28 GHz chamber the increase in local temperature was greatest at 9.5 mW/cm^2, was least at sham, and there was little difference between the other

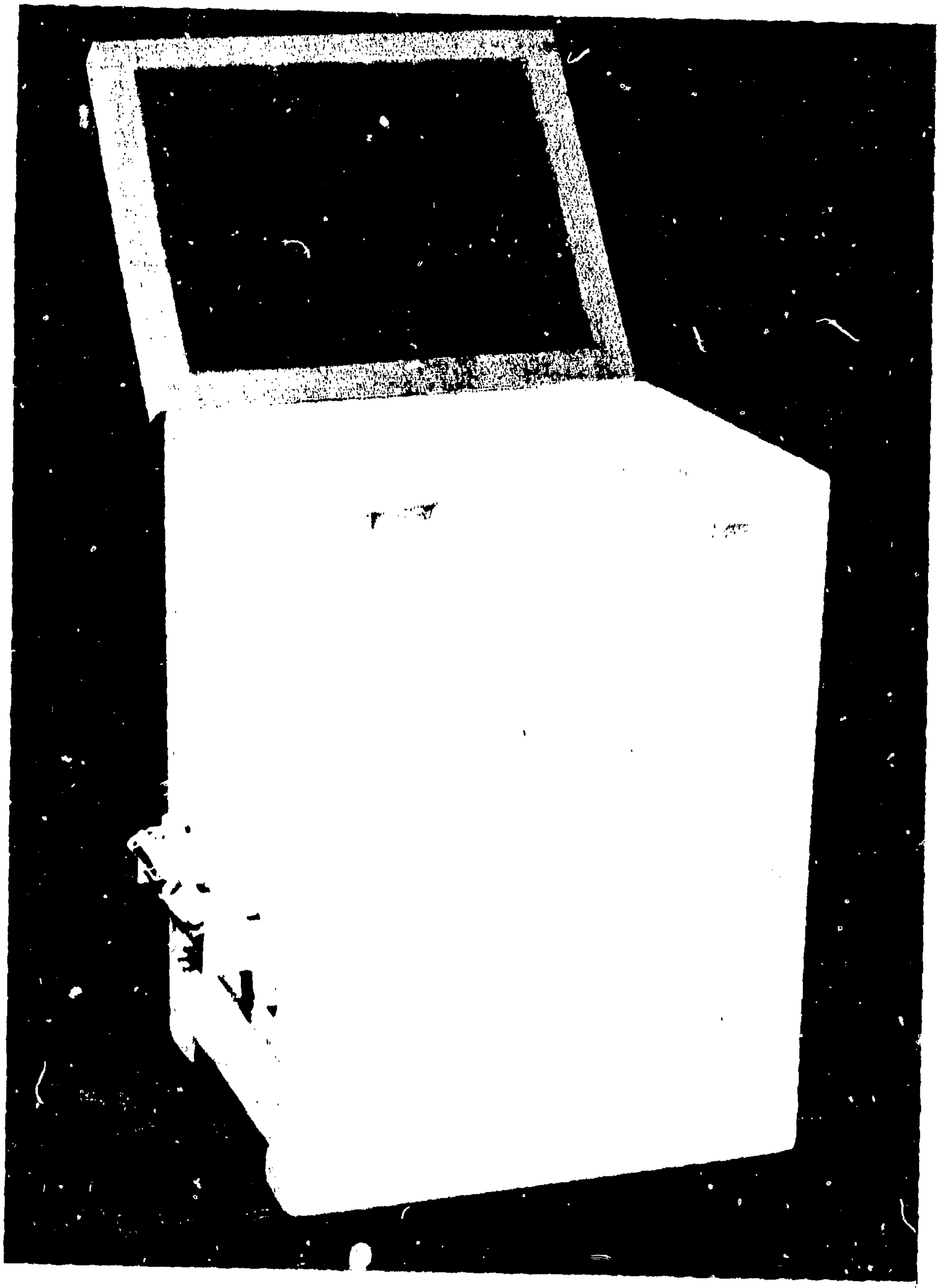

Figure 2. Styrofoam rat conditioning box.

power densities. In the 5.62 GHz chamber the increase in local temperature was least at the highest power density (48.5 mW/cm^2) and at sham; the largest increase was at 31.5 mW/cm^2. These pattern differences were caused by differences in distance from the energy absorbing rear wall (the absorber heated) and differences in air flow around the operant box as its position was varied. No relationship between behavior and local temperature changes was evident in either chamber. Relative humidity of input air averaged 51.65 ± 4.91 percent in the 1.28 GHz chamber and 50.34 ± 2.81 percent in the 5.62 GHz chamber. White noise and the ventilation fans provided a masking noise of 78 dB C in each chamber. Computer-operated control and recording equipment were located in an adjoining room.

METHOD

Initial training was in an operant conditioning box of hard plastic walls located in an isolation chamber remote from the microwave chambers. After stable performance developed, the conditioning box was replaced with one of Styrofoam. Following the development of stable behavior in the new box, the entire arrangement was relocated from the isolation chamber to the anechoic microwave-exposure chamber. Ninety 40 min sessions transpired over the course of training prior to microwave exposure. All sessions occurred daily, five days a week. A total of 183 sessions were devoted to the 5.62 GHz exposure portion of the study followed by 62 sessions in the 1.28 GHz portion. The two portions of the study were separated by 90 days.

The training procedure followed the method of approximations and is detailed in a previous report (3). The final performance required the rat to depress the right lever which produced a 0.7-s 1000 Hz tone (62 dB) or a 10-s 1250 Hz tone (70 dB). Right-lever responses were reinforced with the higher frequency tone on the average of once every 20-s (variable interval, VI-20-s) otherwise the lower frequency tone was presented. If the left lever was depressed during the high tone, the tone would go off and a 45-mg Noyes' rat food pellet (The P.J. Noyes Co., Lancaster, NH) was delivered to the hopper. Left-lever responses in the absence of the high tone produced a 10-s period in which right-lever responses produced only the 0.7-s lower frequency tone. If the left lever was not pressed during the 10-s presence of the high tone, the tone would go off and the VI-20-s schedule would recycle. The schedule generated a very high and stable response rate on the right lever during the 40-min sessions.

The rats were initially exposed to average incident power densities of 0 (sham), 7.5, 11.5, 16, 26, 31.5, 38.5, 42, and 48.5 mW/cm^2 at a frequency of 5.62 GHz. These values were arrived at by positioning the conditioning box at various axial distances from the horn and by utilizing the 0.5 and 2 μs pulse durations. At 1.28 GHz the animals were exposed to 0 (sham), $\leq$1, 5.5, 9.5, 10, and 15 mW/cm^2 by positioning the box at various axial distances from the horn. The power density of $\leq$1 mW/cm^2 was arrived at by placing a sheet of microwave absorber between the horn and the conditioning box. During a session the rats were exposed for 40 min and immediately removed when the session terminated. Normally, sham exposures preceded and followed irradiation sessions by one day. Prior to irradiation sessions response rates were allowed to return to between-session stability.

Dosimetric measurements were made with a water (normal saline) model exposed at different distances from horn. The container for the water model, shown in Figure 3, consisted of symetric cavities carved into blocks of Styrofoam. When the blocks of Styrofoam were bound together, the resulting cavity was shaped like a standing rat, had a volume of 385 ml, and could be filled with saline or muscle-simulating material. It was exposed to the vertically polarized radiation in the same orientation as the working rat. In this posture the cervical/thoracic region was nearly horizontal and the lumbo/sacral region was nearly vertical. Temperature changes in exposed saline were measured and the SAR was calculated using the heating-curve technique (1). SAR was also determined for the case in which the cavity was filled with a muscle-simulating material. A four-lead high resistance thermistor (Vitek, Inc., Boulder, CO) was used to obtain the temperature measurements. For the muscle-simulating material. in which the heat could not be readily homogenized by convection, temperature measurements were made at twelve different locations.

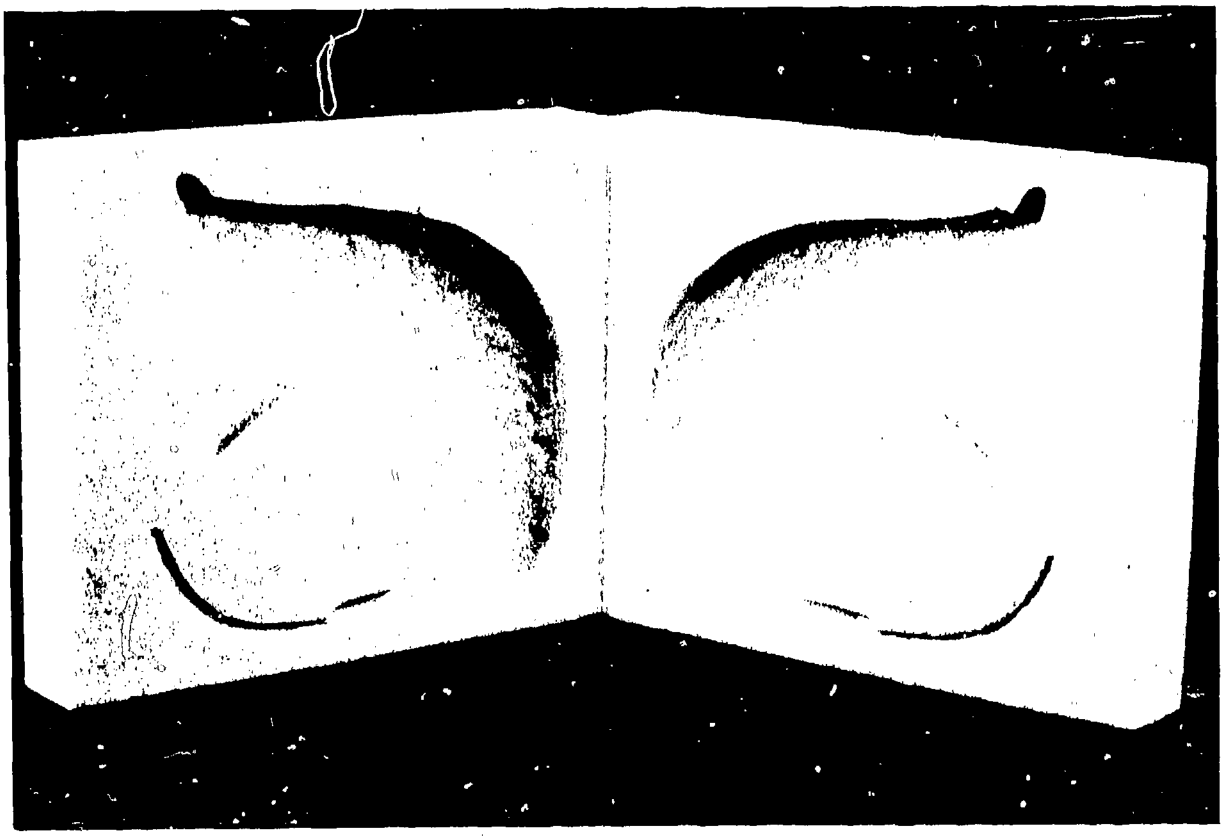

Figure 3. A Styrofoam block containing the rat-shaped cavity used for calorimetric measurements. This cavity was filled with saline or muscle-simulating material and thermistors inserted from the top or back.

RESULTS

DOSIMETRY

The averaged specific absorption rate (SAR), calculated from temperature measurements on the water model, and normalized per unit of incident power density, was 0.25 ± 0.01 (W/kg)/ (mW/cm^2) (mean ± S.D., n = 7) at 1.28 GHz irradiation and 0.19 ± 0.03 (W/kg)/ mW/cm^2) (n = 25) at 5.62 GHz irradiation. These values compare favorably with those calculated for prolate spheroidal models of rats at E and H polarizations (6, p 95).

The localized SAR as measured at the twelve different locations in the muscle-simulating material is shown in Figure 4 along with a diagrammatic representation of the measurement locations in the rat model. The rat model was irradiated with the direction of propagation coming from its right-hand side. The left side of the abscissa in each graph of Figure 4 is nearest to the source of irradiation. The figure illustrates that most of the energy absorbed at 5.62 GHz was in the front surface of the model whereas at 1.28 GHz more energy was absorbed near the rear surface in the head and hip areas. The largest energy distribution differences between exposures at these two frequencies were also in the head and hip areas, and these differences were most pronounced in the model's head.

BEHAVIOR

The response rate on the observing lever (right lever) was consistently disrupted in all eight subjects at 15 mW/cm^2 during exposure to 1.28 GHz microwaves. Typically, the disruption was seen in an overall reduced response rate, long pauses unrelated to food pellet delivery, and in many animals a complete cessation of responding after 15 to 20 minutes of exposure. Similar effects were observed in seven of the rats when exposed to 5.62 GHz microwaves at power densities of 26 mW/cm^2 or greater. To consistently affect the behavior of all eight subjects at this higher frequency a power density of 38.5 mW/cm^2 was necessary. The averages of observing-response rates at the two frequencies and various power densities are illustrated in Figure 5 as ratios of exposed to sham conditions. The points represent means and the bars show one standard error of the mean on each side of the mean. The line at 1.0 indicates that irradiated and sham levels of responding are the same. Figure 5 demonstrates that average observing-response rates during exposure sessions were substantially different from sham sessions beginning at 10 mW/cm^2 in the case of 1.28 GHz and at 26 mW/cm^2 in the case of 5.62 GHz. In both cases responding tended to be increasingly depressed with increased power density.

At both frequencies individual differences existed in an animal's susceptibility to the microwaves. For example, at 1.28 GHz seven of eight rats decreased observing-response rates when exposed to a 10 mW/cm^2 level, yet only one rat was undeniably affected at 9.5 mW/cm^2. Three rats exposed to the lower frequency showed small observing-response rate decreases when first irradiated at 5.5 mW/cm^2, but these decreases did not appear when later irradiated at the same power density. Similar idiosyncratic effects were observed at 5.62 GHz exposures. At the higher frequency one rat was

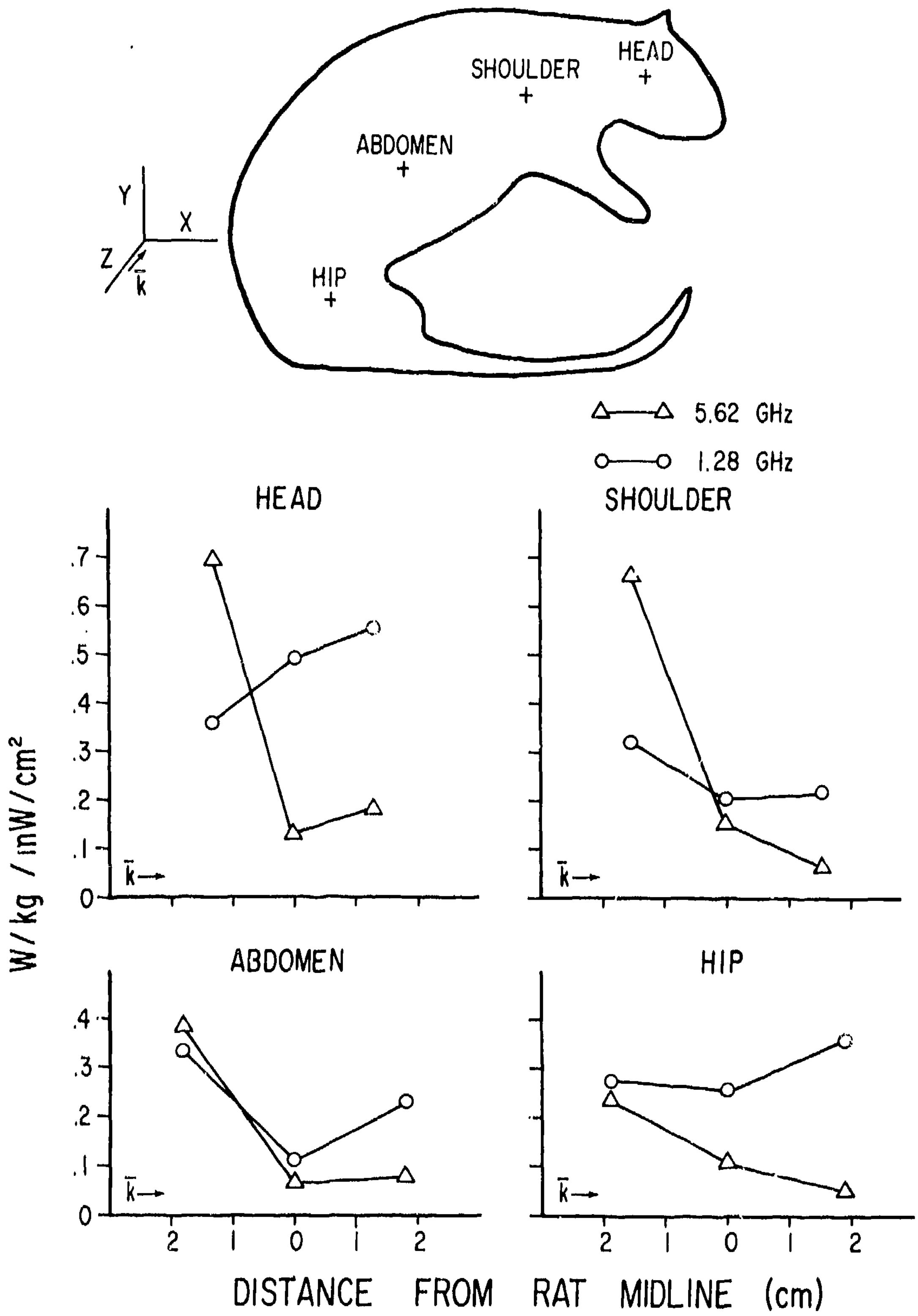

Figure 4. Outline of the rat model showing locations of the temperature measurements. The graphs present the normalized SAR (ordinate) at three axial distances (abscissa) in each location for irradiation at 1.28 GHz (circles) and at 5.62 GHz (triangles).

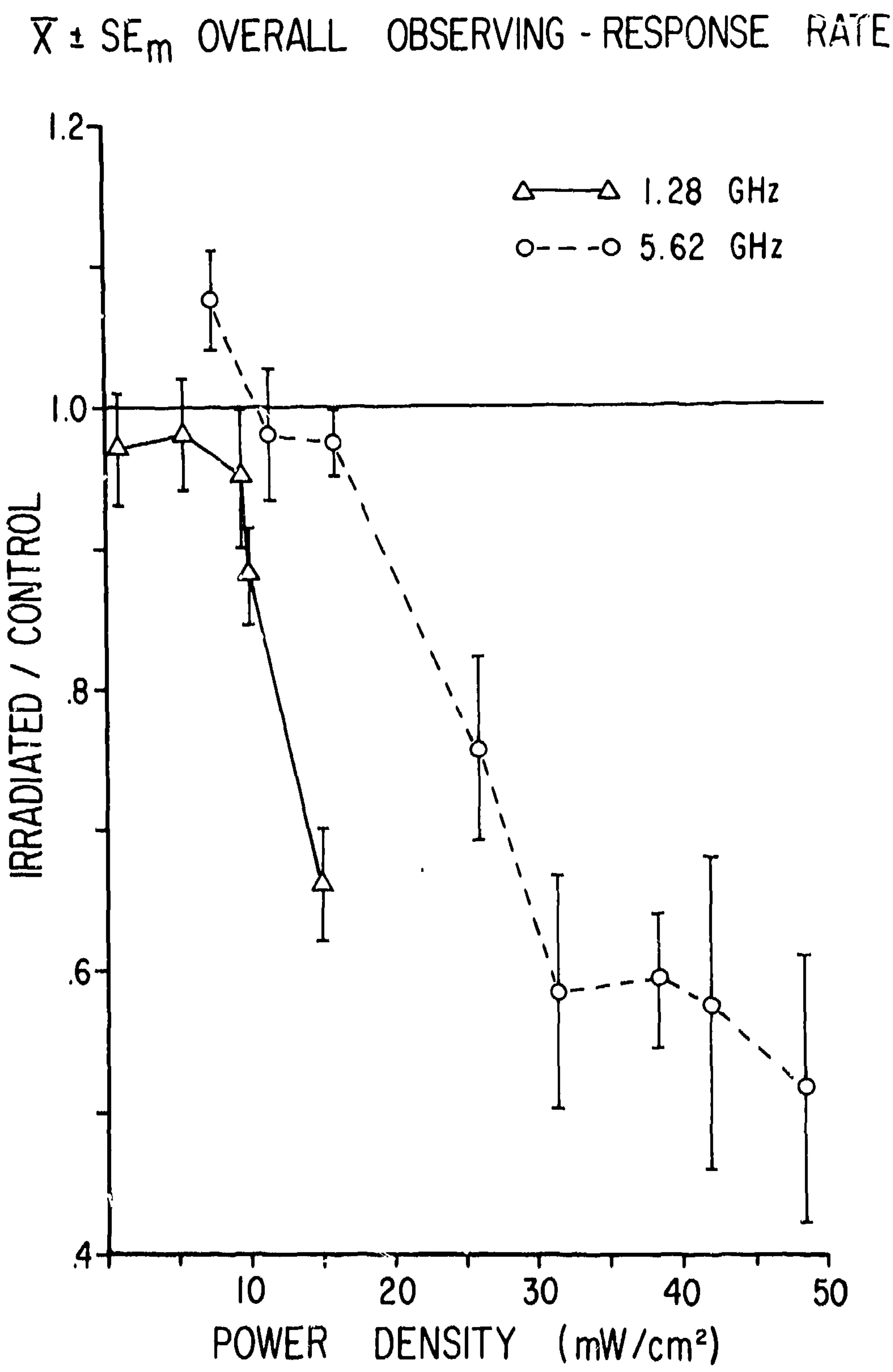

Figure 5. Right-lever (observing) response rate plotted as a ratio of irradiated session means to sham (control) session means including the standard error of these ratios. A ratio of 1.0 (horizontal line) denotes no difference between sham and irradiated conditions.

slightly affected at 16 mW/cm^2 and one was not bothered until exposed to a power density of 38.5 mW/cm^2.

Examples of cumulative records that illustrate the decrease in observing-response rate as a function of duration of exposure are shown in Figures 6, 7, and 8. Figure 6 contains sham and 1.28 GHz exposure records of rat 9, an animal that responded at high rates. The right-hand margin lists the power densities, and the small numbers in the left upper corner of each set of records denote the session number. Each record is of an entire 40-min session. The response pen reset at 280 responses or at the end of a session. The pen was momentarily deflected with each reinforcer and stepped upwards with each observing-response. The pen on the horizontal line below the response record was deflected when the high tone indicating food availability was present. As seen in Figure 6, no obvious effect occurred until a power density of 15 mW/cm^2 was used, and after 20 min the animal completely stopped responding. In addition, at 15 mW/cm^2 this rat frequently failed to make a detection-response to the appropriate tone, thereby foregoing a food pellet as indicated on the horizontal line by the longer pen deflections prior to the cessation of responding.

Figure 7 contains similar records of rat 10 when exposed to sham and 5.62 GHz microwaves. In this figure the lower horizontal line is used only for aligning the response records. The entire series of exposures is not shown; only samples covering most of the series are shown because of space limitations. There is a gradual decrease in responding with exposure to 26 mW/cm^2, followed again by a complete cessation of responding after about 20 min of exposure.

Some of the animals habituated to repeated microwave exposure as shown in Figure 8 for rat 7. This figure contains consecutive sham and exposure cumulative records obtained during exposure to 15 mW/cm^2 of 1.28 GHz irradiation. At the first exposure, session 23, a gradual decrement in rate was followed by a complete cessation of responding within 15 min. After a recovery day the exposure was repeated and responding was less disrupted. Two intervening sham sessions occurred, and the third exposure was even less disruptive at session 28.

Responding incorrectly on the left lever was affected basically in the same manner as observing-responses at both microwave frequencies. These responses could be considered false detections (left-lever responses in the absence of the food-availability tone), and their frequency and that of correct detections decreased with increases in power density, as shown in Figure 9. This decrease was substantial at levels of 10 mW/cm^2 and above during exposure to 1.28 GHz microwaves and at levels of 26 mW/cm^2 and above during exposure to 5.62 GHz microwaves. When analyzed as a function of total observing-responses, there was actually an increase in the mean proportion of false detections as power density increased even though the absolute number of false detections decreased. The extent of the proportional increase in false detections is seen in Figure 10, which shows the means and standard errors of the means at the two frequencies as a function of power density. Although these incorrect responses only increased slightly at 1.28 GHz, the increase at 5.62 GHz was well defined. The correlation coefficient

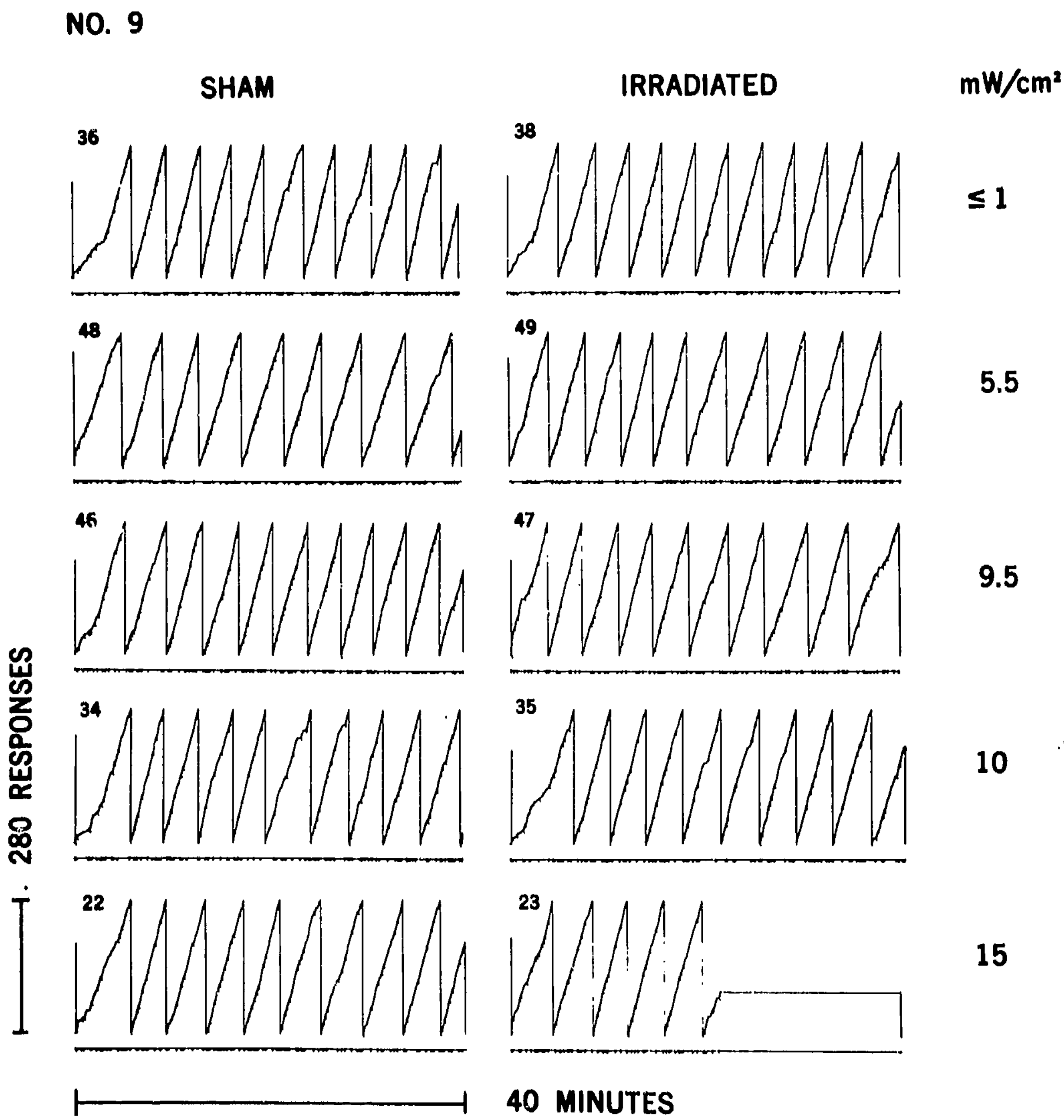

Figure 6. Sham and 1.28 GHz exposure cumulative records of observing-responses for rat 9. Power densities are indicated at the right of each row of records. The smaller number at the left of each session's recording is the session number. Responses are shown on the left and time is indicated at the bottom.

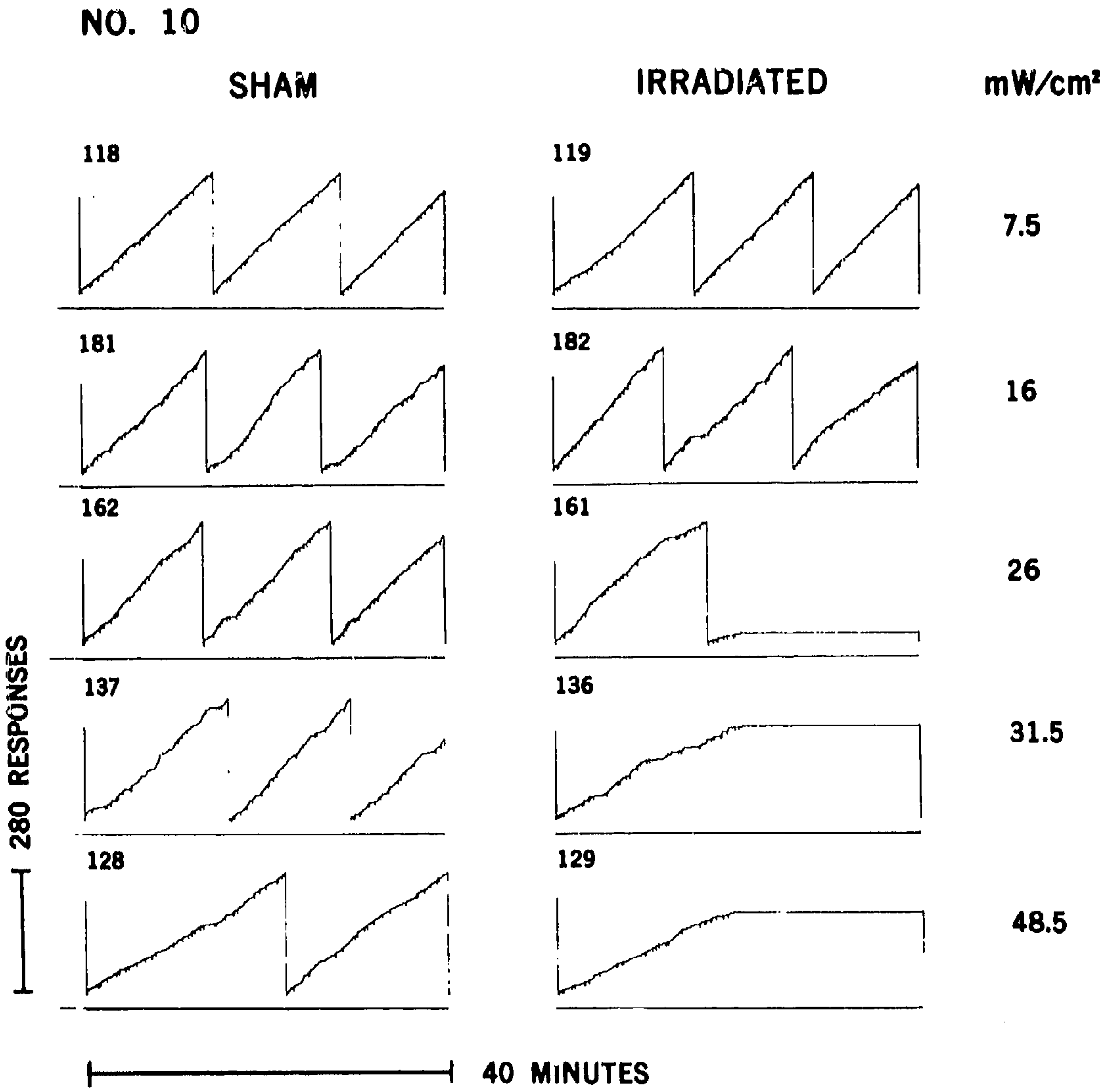

Figure 7. Cumulative observing-response records of rat 10 when exposed to sham and 5.62 GHz conditions. Power densities are shown on the right and session numbers are in the upper left corner of each recording.

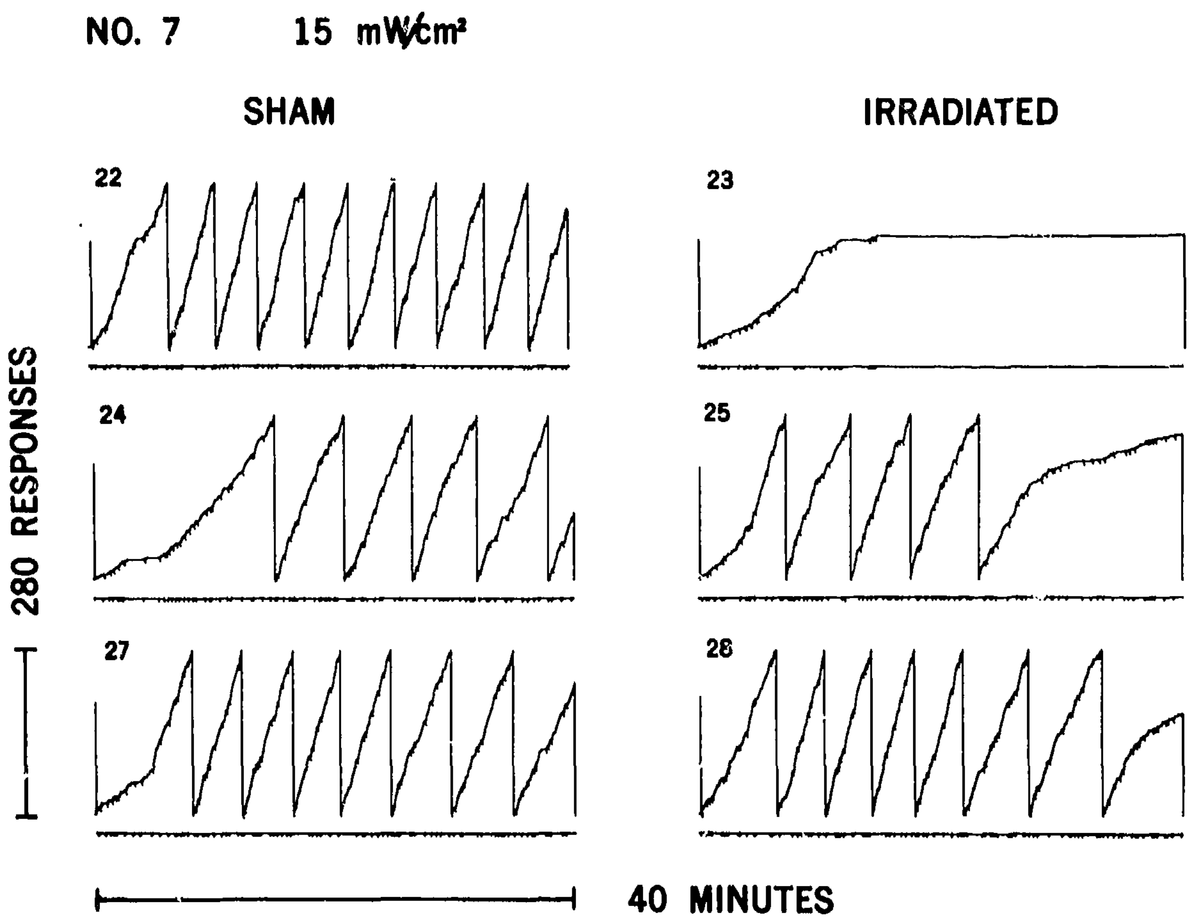

Figure 8. Cumulative observing-response records of rat 7 showing consecutive exposures to sham and 15 mW/cm^2 power densities at 1.28 GHz. The numbers at the upper left of each record are session numbers.

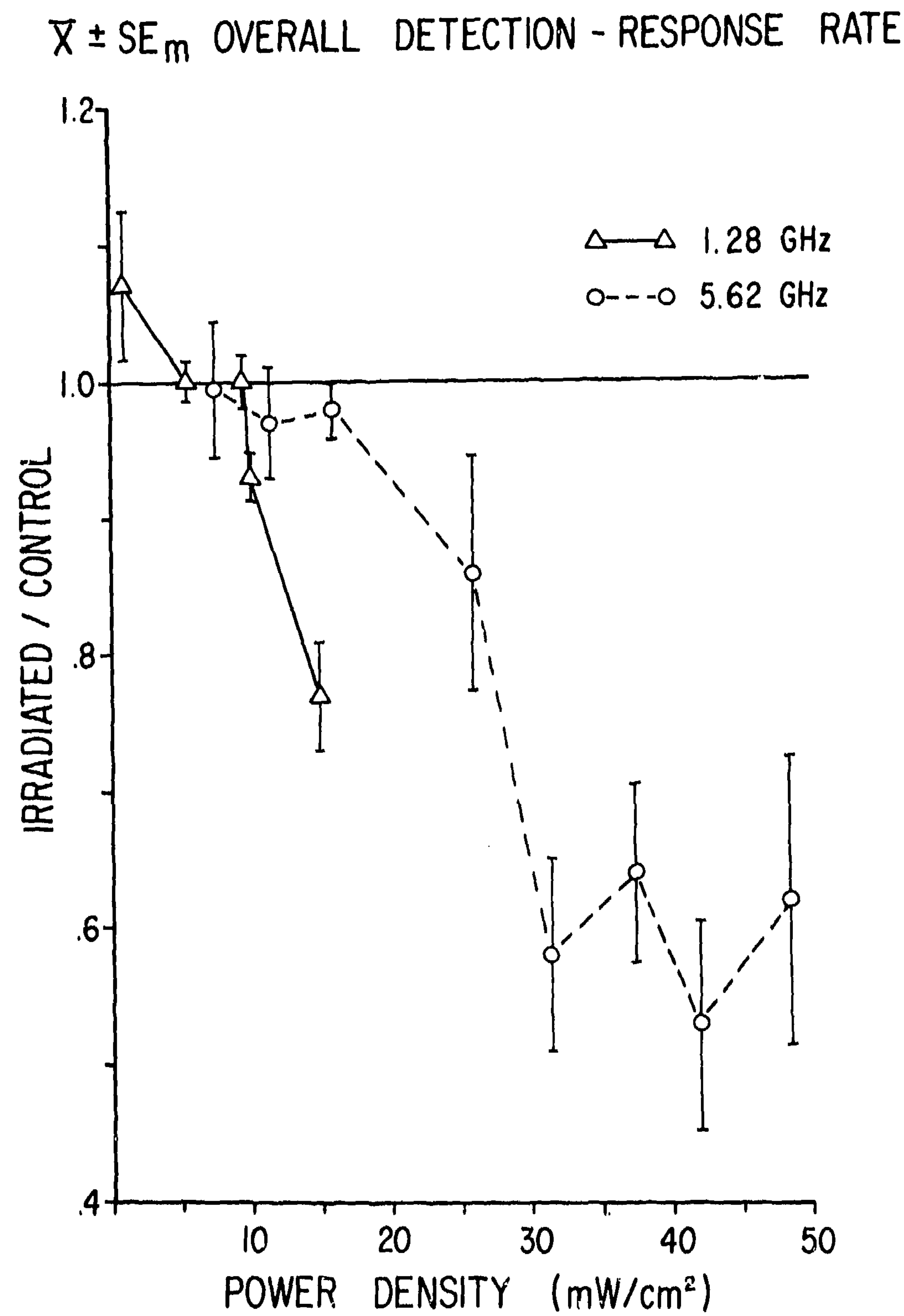

Figure 9. Detection (left lever) response rate shown as a ratio of irradiated session means to sham session means. Each point represents the data from 3 rats.

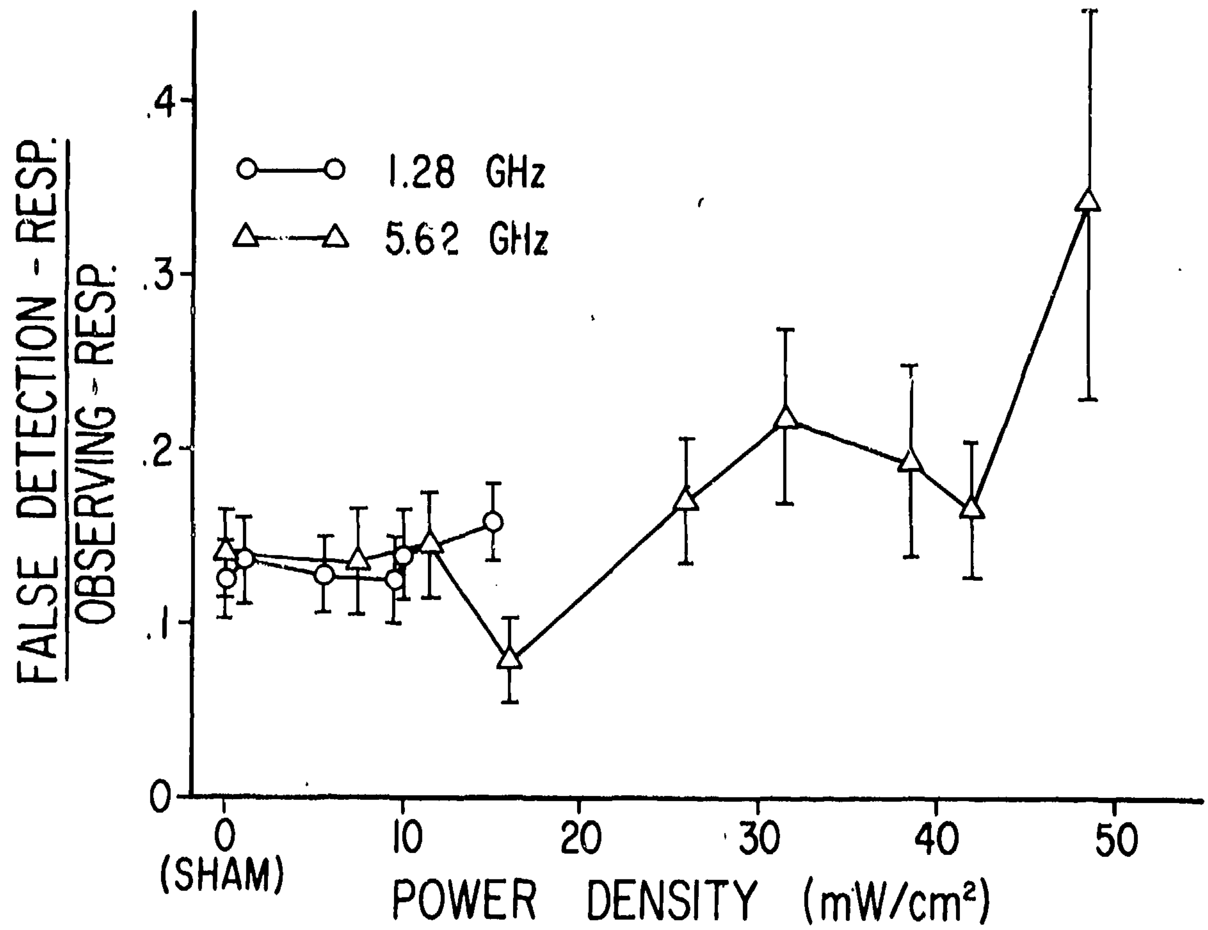

Figure 10. The ratio of false detection-responses to observing-responses shown as a function of power density at the two microwave frequencies.

between power density and false detection-responses was +.61 at 1.28 GHz (not significant at $p < .05$, $df = 4$) and +.72 at 5.62 GHz (significant at $p < .05$, $df = 7$). It must be noted that these increases are relative. The total detection-responses decreased with power density increases as did all responses; it is just that the relative number of false detections increased with increases in power density.

Another effect of the microwaves was seen on the pause time following a reinforced detection-response. This time period increased as power density increased; the result is shown in Figure 11. Like many other measures the increase was not consistently seen until power densities reached 10 mW/cm^2 at 1.28 GHz (a small, but reliable difference) and 26 mW/cm^2 at 5.62 GHz. Nevertheless, in terms of averages, there was an increase in the post-reinforcement-pause time even at 16 mW/cm^2 at 5.62 GHz irradiation.

Neither the latency to make a detection-response, a measure of reaction time traditionally used as an indication of vigilance decrement, nor the probability of detection-responses showed consistent between-subject effects of microwave exposure. In those rats who failed to make detection-responses in the presence of the appropriate signal, the decrease in detection-response probability occurred near the end of exposure sessions. No overt physiological effects of hyperthermia, including wetting of the fur with urine or saliva, were observed in the rats at either microwave frequency.

DISCUSSION

Behavior is a reflection of many physiological processes in an animal and as such includes not only the effects of an environmental change but also the animal's ability to homeostatically compensate for disruptive consequences of environmental changes. Hence, it is not surprising that the rats in the present study showed no consistent behavioral changes at power densities below 10 mW/cm^2 at either microwave frequency used. These animals were food deprived and thus were occupied on a task that not only produced food but also required relatively undivided attention to successfully operate. The fact that most of the subjects showed behavioral disruptions at 10 mW/cm^2 when exposed to 1.28 GHz and showed no behavioral change until exposed to 26 mW/cm^2 at 5.62 GHz is surprising. The averaged SAR (4.9 W/kg) at the 5.62 GHz disrup ing level concurs with previous results at 2.45 GHz, but the averaged SAR (2.5 W/kg) at the disruption level of 1.28 GHz is much lower. There are several possible explanations for these differences; the primary one is founded on the unique differences in energy distribution at the two frequencies. Although a higher total SAR was observed at 5.62 GHz, most of the energy was deposited in the outer 5 to 10 mm of the right side of the working rat; whereas at 1.28 GHz a concentration of energy deposition occurred throughout the rat and especially in its head.

At 5.62 GHz the average SAR (4.9 W/kg) corresponding to initial behavioral disruption in the present study agrees with findings in several other studies, although these other studies exposed rats to 2.45 GHz CW irradiation. Some of the similarities are remarkable. Lotz and Michaelson (12) discovered that the threshold for adrenal-axis stimulation corresponded to an SAR of 4.8 W/kg, and de Lorge (4) found the threshold for disruption of rhesus monkeys on a vigilance task to be approximately 4.7 W/kg [according to calculations

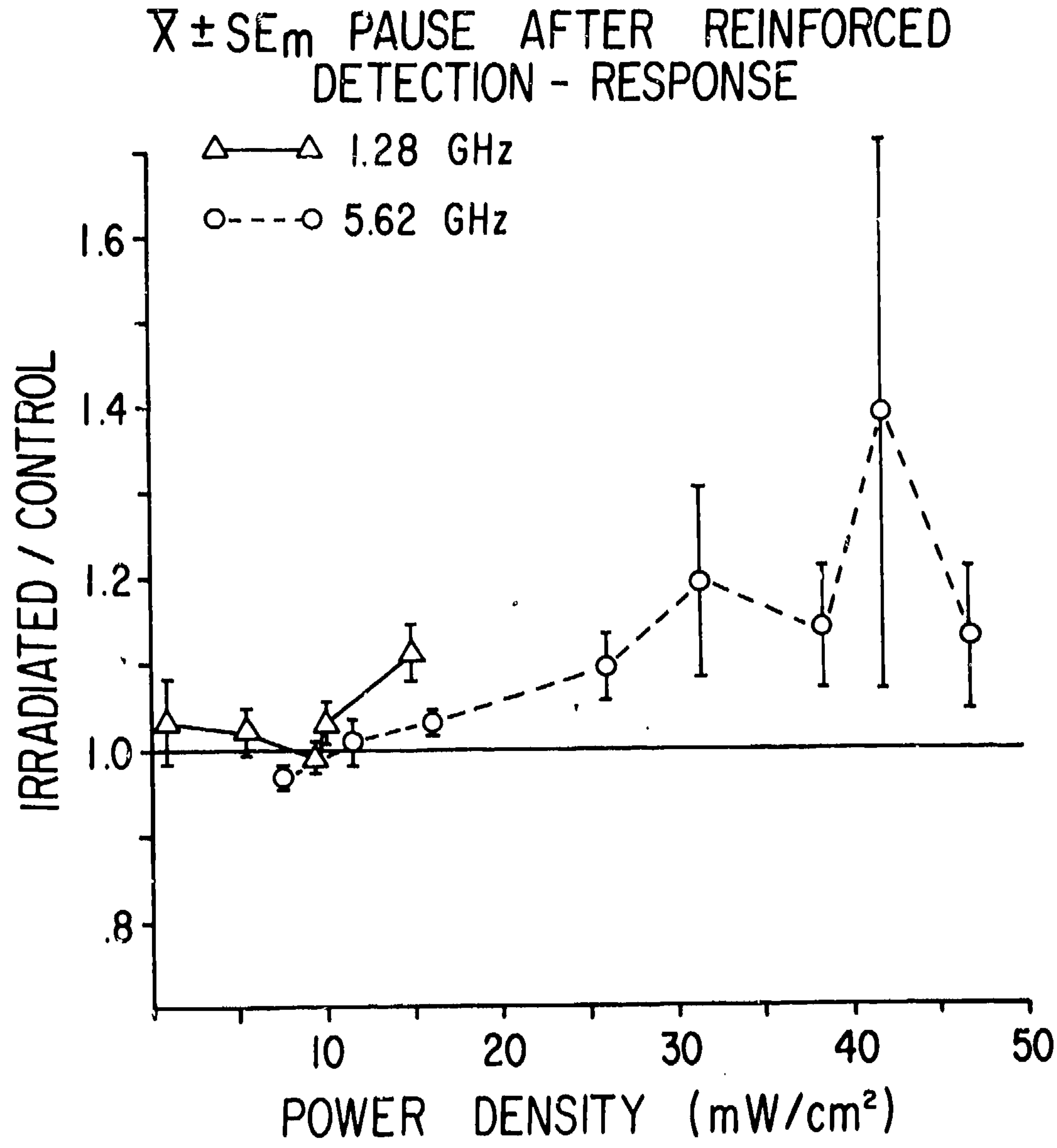

Figure 11. Post-reinforcement pause as a function of power density and microwave frequency. The pause is shown as a ratio of means during irradiation sessions to sham session means.

based on Durney et al. (6)]. Another study by de Lorge (5), with squirrel monkeys on the same task, resulted in finding a threshold at 2.5 W/kg, calculated for K-polarized incident intensity of 45 mW/cm^2. The anomalously low squirrel monkey SAR at this power density was probably due to the bending forward of the monkey in its restraint chair, thereby orienting in more of an E polarization than a K polarization. According to Durney et al. (6), our sitting squirrel monkey at E polarization would have an SAR of 4.5 W/kg. Finally, another study in our laboratory (14) found operant behavior in rats to be disrupted at 28 mW/cm^2 at 2.45 GHz. This power density corresponds well with that in the Lotz and Michaelson study (30 mW/cm^2) which was said to produce an SAR of 4.8 W/kg. In all of these 2.45 GHz studies the average rectal temperature change at the point of behavioral disruption was 1° C, or more, above sham exposure temperatures.

The averaged SAR (2.5 W/kg for 7 of 8 subjects) corresponding to behavioral disruption when the rats were irradiated with 1.28 GHz microwaves differs considerably from reported SARs in similar studies. In fact, two studies with rats found behavioral changes related to SARs of 8.4 and 9 W/kg (9, 11) although different frequencies were used, 918 and 2450 MHz, respectively, as were different exposure conditions, near and far field. The present authors are not familiar with any rat experiments using 1.28 GHz or L band irradiation wherein rectal temperature was also obtained along with behavioral changes.

The primary effect of microwave irradiation, a decrease in response rate, is a typical finding in similar studies [see for example (10)]. The interpretation of this effect, however, has differed considerably. The present authors emphasize that the decrease in observing-response rate is a form of disruption of ongoing behavior and not necessarily a symptom of the perturbation of more covert events; i.e., internal "timing" mechanisms. Traditionally when physical agents interfere with free-operant behavior, the direction of interference is a function of the reinforcement schedule. When high rates of responding are generated by a schedule, lower rates occur with the introduction of physical agents. When low rates of responding are generated by a reinforcement schedule, disruption is typically seen by the occurrence of higher rates [see for example (16)]. Exceptions do occur, but they are rare where the reinforcement schedules normally generate constant response rates.

Evidence of something other than a simple reduction of response rate is seen in the positive correlations between power density and incorrect left-lever responses (false detections). Here, while both left- and right-lever response rates showed decreases, the relative frequency of false detections increased. It was expected that the relationship would remain constant because of the chained nature of detection-responses and food signals. A similar, but less defined result was obtained when squirrel monkeys, working the same task with visual signals (5), were exposed to 2.45 GHz microwaves (120 Hz, 100 percent modulated sine wave). The effect, then, is probably not caused by a confusion of the tones produced by the microwave auditory effect (7) obtained with pulsed radiation. In both the present experiment and the previous one with squirrel monkeys this relative increase in false detections was seen only at the higher power densities; i.e., those power densities that had an obvious effect on the observing-response rate.

CONCLUSIONS

The behavioral disruption produced by electromagnetic radiation in the present study was almost certainly related to the thermal consequences of such radiation, either extensive surface heating or "hot spots." No evidence for the ephemeral "non-thermal" effects of microwaves was obtained. The absorbed energy measurements on models illustrate that even though less average energy may be deposited in the rat at 1.28 GHz, more heat is produced in other than surface areas. This distribution of heat obviously was more disruptive of behavior than the distribution of heat produced at 5.62 GHz although a higher whole-body SAR was evident at the latter frequency when behavior was disrupted.

No evidence of cumulative effects of repeated exposure to microwaves was observed in this study. On the contrary, it was found that repeated exposures allowed the animals to be less perturbed by the irradiation. This observation agrees with similar results wherein 2.45 GHz microwaves were used in rats and monkeys (4, 5, 14). Because body temperatures were not obtained in the present study, conclusions regarding temperature change and temperature adaptation cannot be drawn.

Finally, the present study along with the experiment by Sanza and de Lorge (14) shows an interesting consistency when used with the curves of average SAR produced by Durney et al. (6) for prolate spheroidal models of rats. That is, at 2.45 GHz and higher frequencies the average SAR for rats aligned with E polarization is relatively constant, whereas, at 1.28 GHz more energy is deposited in the rat for the same amount of incident power density. Hence, at 1.28 GHz less incident power density should produce the same amount of behavioral disruption based on the concept of an SAR threshold.

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: NAMRL—1264 (14)

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): AN EXPERIMENTAL ANALYSIS OF AN OBSERVING-RESPONSE IN RATS EXPOSED TO 1.28 AND 5.62 GHz MICROWAVE IRRADIATION (6)

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s): (10) John O. de Lorge [redacted] Clayton S. Ezell

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS: Naval Aerospace Medical Research Laboratory, Naval Air Station, Pensacola, Florida 32508

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: (17) MF58 524 015 0037

11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Medical Research and Development Command, National Naval Medical Center, Bethesda, MD 20014

12. REPORT DATE: (11) 5 Nov[redacted]79

13. NUMBER OF PAGES: 23

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (12) 26

15. SECURITY CLASS. (of this report)

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

(16) F58524

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Operant behavior, Microwaves, Vigilance, Rats

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Naval communications and weapons systems use a variety of microwave producing devices. Frequently fleet personnel may be exposed to the radio-frequency irradiation emanating from such devices. Current scientific reports indicate that biological changes can be produced by nonionizing electromagnetic irradiation and that complex behavioral effects are predominant among these changes.

A Few studies of the biological effects of microwave irradiation have

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20. ABSTRACT (Continued)

investigated complex behavior in non-human organisms. One human behavior easily simulated in other animals is monitoring performance, otherwise known as observing-behavior or performance on a vigilance task. This task requires an animal to respond, thereby producing one or more stimuli. When the stimuli change, the animal has to report the change to obtain a reinforcer. In the present study the effects of two different microwave frequencies (1.28 and 5.62 GHz) on observing-behavior in rats were investigated.

At 1.28 GHz the observing-response rate was consistently affected at a power density of 15 mW/cm2 in all eight rats while at 5.62 GHz the observing-response rate was not consistently affected until the power density approximated 26 mW/cm2. Measures of the averaged specific absorption rate (SAR) in a rat model of simulated muscle tissue illustrated a distribution difference at the two different frequencies. The SAR distribution within the model's head at 1.28 GHz was the inverse of the distribution in the head at 5.62 GHz. It was concluded that the rat's behavior was more easily disrupted at 1.28 GHz than at 5.62 GHz because of the deeper penetration of energy at 1.28 GHz and differences in energy distribution at the two frequencies.

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EXPOSED TO 1.28 AND 5.62 GHz MICROWAVE IRRADIATION

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MF58.524.015-0037

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SUMMARY PAGE

THE PROBLEM

Naval communications and weapons systems use a variety of microwave producing devices. Frequently fleet personnel may be exposed to the radio-frequency radiation emanating from such devices. Current scientific reports indicate that biological changes can be produced by nonionizing electromagnetic radiation and that complex behavioral effects are predominant among these changes.

Few studies of the biological effects of microwave radiation have investigated complex behavior in non-human organisms. One human behavior easily simulated in other animals is monitoring performance, otherwise known as observing-behavior or performance on a vigilance task. This task requires an animal to respond, thereby producing one or more stimuli. When the stimuli change, the animal has to report the change to obtain a reinforcer. In the present study the effects of two different microwave frequencies (1.28 and 5.62 GHz) on observing-behavior in rats were investigated.

FINDINGS

At 1.28 GHz the observing-response rate was consistently affected at an exposure power density of 15 mW/cm^2 in all eight rats while at 5.62 GHz the observing-response rate was not consistently affected until the power density approximated 26 mW/cm^2. Measurements of the localized specific absorption rate (SAR) in a rat-shaped model of simulated muscle tissue revealed differences in the absorption pattern for the two frequencies. The SAR within the model's head at 1.28 GHz was higher on the side opposite the irradiation source. The SAR distribution was exactly opposite at 5.62 GHz. It was concluded that the rat's behavior was more easily disrupted at 1.28 GHz than at 5.62 GHz because of the deeper penetration of energy at 1.28 GHz and the differences in energy distribution at the two frequencies.

ACKNOWLEDGMENTS

Dr. R. G. Olsen's assistance in various phases of this study is greatly appreciated as is the assistance of T. Griner and D. Prettyman. We also wish to thank D. Early for her assistance in preparation of this report.

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The animals used in this study were handled in accordance with the Principles of Laboratory Animal Care established by the Committee on the Guide for Laboratory Animal Resources, National Academy of Sciences-National Research Council.

INTRODUCTION

This report is concerned with the investigation of behavioral effects of microwaves produced by radar sources representative of those currently used in the Navy. The investigation was prompted partially by the extreme difference between safety standards for microwave radiation exposure in the Soviet Union and in the United States (15), and partially by the sparsity of definitive, parametric experiments on behavioral effects of such exposure.

Our contribution to the resolution of these problems has been a series of studies defining the relationship between the body mass of a mammal and the microwave power density necessary to disrupt behavior on a complex operant task analogous to tasks engaged in by humans. It is possible that analogues of human behavior may be very susceptible to microwave radiation. One such parallel is observing-behavior or performance on a vigilance task. In experiments on human vigilance, subjects are presented aperiodically with superthreshold stimuli to which they are instructed to respond differentially (13). The stimuli are called "signals" and responses to them are called "detections." Holland (8) developed a technique for controlling human vigilance by having the subject illuminate a meter dial before reporting whether the needle on the dial was offset (detection). The response, a depression of a telegraph key which illuminated the meter dial, was called the "observing-response." Holland's experiments showed that detections functioned as reinforcement for observing-responses, and that observing-behavior was controlled by events similar to the controlling events of "vigilance" behavior in its traditional meaning. The empirical content of the question whether an observing-response represents "true vigilance" is largely a matter of whether neural events affecting discrimination are controlled by reinforcement or other variables in the same manner as overt observing-responses.

The experiments reported here were designed to produce observing- and detecting-behavior in rats under a schedule similar to those typically employed in human monitoring experiments. Signals occurred aperiodically if the rat continually monitored the stimuli, and a detection response in the presence of the transient signals resulted in delivery of a food pellet. The vigilance task herein reported is described in operant conditioning terminology as a heterogenous chained schedule of reinforcement, Chain VI 20-sec, FR 1 with a limited hold of 10 sec (2).

Previous experiments (4, 5, 14) in this series of studies have provided sufficient data on the rat, squirrel monkey, and rhesus monkey to construct a preliminary scale based on body mass and behavioral changes at one microwave frequency, 2.45 GHz. The purpose of the present experiments was to discover the power density at which rats working a vigilance task would have their behavior disrupted when exposed to two other frequencies, 1.28 and 5.62 GHz.

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PROCEDURE

SUBJECTS

Eight male rats of the Long Evans strain obtained from the Charles River colonies served as subjects. The mean body mass of the food-deprived rats during the 5.62 GHz exposure phase (the initial phase) of the study was 362 ± 16 g. During the 1.28 GHz exposure phase it was 400 ±18 g. These maintenance levels were 90 and 88 percent of their free-feeding body mass during the 5.62 GHz and 1.28 GHz exposures, respectively. Water was continuously available in the home cages.

APPARATUS

Two microwave anechoic exposure chambers, one for 1.28 GHz and one for 5.62 GHz, were used. The exterior dimensions of the lower-frequency chamber were 3.40 m long x 2.20 m wide x 2.35 m high. The exterior dimensions of the higher-frequency chamber were 2.54 m long x 1.94 m wide x 2.43 m high. The chamber interiors were shielded with copper and lined with 20-cm pyramidal absorber (AAP-8) obtained from Advanced Absorber Products, Amesbury, MA. Inside each chamber were two small audio-speakers, a closed-circuit TV camera, a 100 W incandescent lamp, a 25 W incandescent lamp, and a Styrofoam stand for holding the operant conditioning box. The 100 W lamp, TV camera, and speakers were located above and behind the microwave horn at a far end of each chamber. The chambers were ventilated at an air exchange rate greater than 28 m^3 per minute, and the operant conditioning box was placed in the center of the air flow. The 25 W lamp was centered 57 cm directly over the conditioning box and was illuminated at the start of and during a session. A schematic of the 1.28 GHz chamber is shown in Figure 1. The higher-frequency chamber is basically identical except for the differences in dimensions.

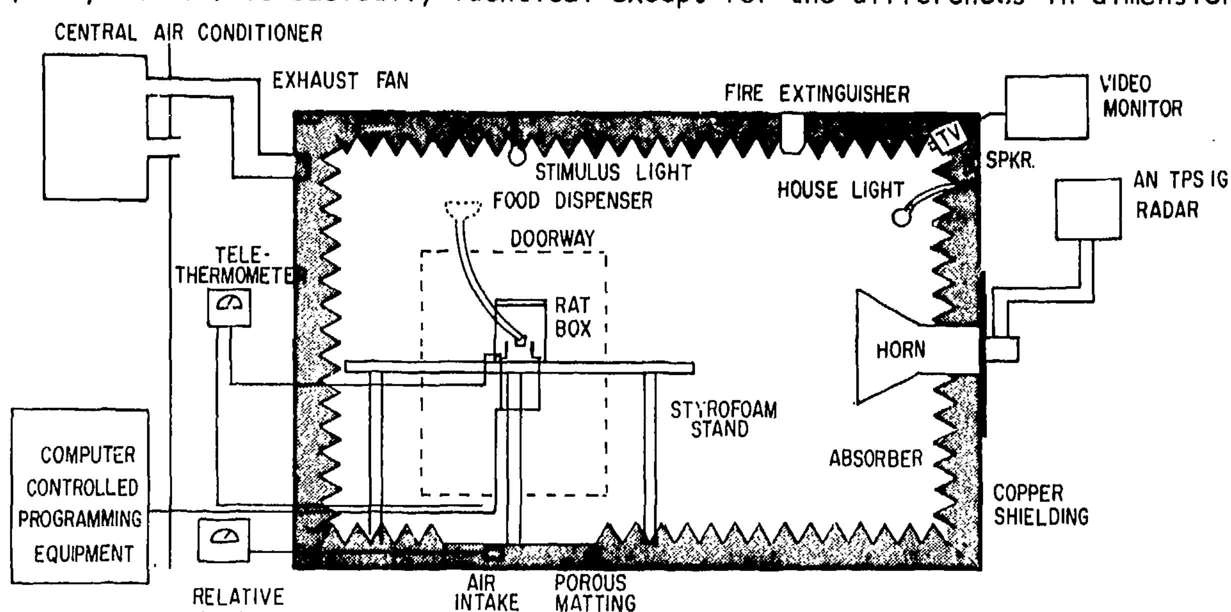

Figure 1. Diagram of the 1.28 GHz exposure chamber. The food dispenser was located outside of the chamber.

A AN/TPS-1G radar set (Hazeltine Corp., Little Neck, NY) provided the 1.28 GHz energy, pulsed at 370 pps with a pulse duration of 3 μs. A AN/SPS-4 radar set (Raytheon Manufacturing Co., Waltham, MA) provided the 5.62 GHz microwaves, pulsed at 662 pps with a pulse duration of either 0.5 or 2 μs. A custom-made horn was connected with a coaxial transmission line to the AN/TPS-1G radar, and a standard gain horn, Narda Model 643 (Narda Microwave Corp., Plainview, NY), was connected with waveguide to the AN/SPS-4. In each chamber the right side of the rat was irradiated while the animal was lever responding. Horizontal propagation was used with the E vector vertically polarized. According to Durney et al. (6), little difference in average energy deposition exists between E and H vectors for a rat exposed to 5.62 GHz irradiation. However, at 1.28 GHz a rat aligned with the E vector could absorb almost twice as much energy as the rat aligned with the H vector. It was unlikely that the rats in these experiments faced the horn because of the configuration of the operant conditioning box and the stringent work requirements.

Incident power density was measured in the absence of the rat with a Narda microline isotropic probe, model 8323, in three dimensions at 5-cm intervals through the center of the operant conditioning box. The power densities reported here refer to the region normally occupied by the rat while in the operant conditioning box. At 1.28 GHz power densities of 0 (sham), ≤1, 5.5, 9.5, 10, and 15 mW/cm^2 were used. At 5.62 GHz power densities of 0 (sham), 7.5, 11.5, 16, 26, 31.5, 38.5, 42, and 48.5 mW/cm^2 were used. All exposures occurred in the far-field region except for the 16 mW/cm^2 level at 5.62 GHz which was at 90 percent of the minimum far-field distance.

The operant conditioning box, shown in Figure 2, was constructed of 2.2 cm thick Styrofoam and was 30 cm deep x 25.5 cm long x 20 cm wide in the interior. The inner walls were coated with a quinine solution painted on a thin layer of epoxy. The quinine was to prevent gnawing by the rats and was not effective with two of the original group of ten animals. A nylon screen covered the top of the box and a polystyrene grid served as the floor. A Styrofoam waste tray was 5 cm below the grid floor. In the right-hand wall of the box (as seen from the horn) two Plexiglas levers 6 mm in diameter projected 5 mm into the interior of the box. Centered between the levers which were 13 cm apart was a polyvinyl food hopper, 1.5 cm in diameter, that projected 1.0 cm into the box. A plastic tube ran from the feeder outside the chamber to the hopper. The levers were 6 cm above the grid floor and the food hopper was 2.5 cm above the grid floor. Wires to the lever microswitches (located outside the box) were fed down the right side of the support stand and out of the anechoic chamber. A Yellow Springs Instruments' tele-thermometer, model 401 (Yellow Springs Instrument Co., Yellow Springs, OH), was oriented axially to the horn and located in the distal wall of the rat box below the floor. Local chamber temperature was recorded with this probe.

Temperature of the air in the chambers varied with building temperature between 23° C and 26.5° C with increases during the day. The local temperature increases during experimental sessions varied from 0.36° C to 1.68° C in the 5.62 GHz chamber and from 0.26° C to 1.20° C in the 1.28 GHz chamber. In the 1.28 GHz chamber the increase in local temperature was greatest at 9.5 mW/cm^2, was least at sham, and there was little difference between the other

Figure 2. Styrofoam rat conditioning box.

power densities. In the 5.62 GHz chamber the increase in local temperature was least at the highest power density (48.5 mW/cm^2) and at sham; the largest increase was at 31.5 mW/cm^2. These pattern differences were caused by differences in distance from the energy absorbing rear wall (the absorber heated) and differences in air flow around the operant box as its position was varied. No relationship between behavior and local temperature changes was evident in either chamber. Relative humidity of input air averaged 51.65 ± 4.91 percent in the 1.28 GHz chamber and 50.34 ± 2.81 percent in the 5.62 GHz chamber. White noise and the ventilation fans provided a masking noise of 78 dB C in each chamber. Computer-operated control and recording equipment were located in an adjoining room.

METHOD

Initial training was in an operant conditioning box of hard plastic walls located in an isolation chamber remote from the microwave chambers. After stable performance developed, the conditioning box was replaced with one of Styrofoam. Following the development of stable behavior in the new box, the entire arrangement was relocated from the isolation chamber to the anechoic microwave-exposure chamber. Ninety 40 min sessions transpired over the course of training prior to microwave exposure. All sessions occurred daily, five days a week. A total of 183 sessions were devoted to the 5.62 GHz exposure portion of the study followed by 62 sessions in the 1.28 GHz portion. The two portions of the study were separated by 90 days.

The training procedure followed the method of approximations and is detailed in a previous report (3). The final performance required the rat to depress the right lever which produced a 0.7-s 1000 Hz tone (62 dB) or a 10-s 1250 Hz tone (70 dB). Right-lever responses were reinforced with the higher frequency tone on the average of once every 20-s (variable interval, VI-20-s) otherwise the lower frequency tone was presented. If the left lever was depressed during the high tone, the tone would go off and a 45-mg Noyes' rat food pellet (The P.J. Noyes Co., Lancaster, NH) was delivered to the hopper. Left-lever responses in the absence of the high tone produced a 10-s period in which right-lever responses produced only the 0.7-s lower frequency tone. If the left lever was not pressed during the 10-s presence of the high tone, the tone would go off and the VI-20-s schedule would recycle. The schedule generated a very high and stable response rate on the right lever during the 40-min sessions.

The rats were initially exposed to average incident power densities of 0 (sham), 7.5, 11.5, 16, 26, 31.5, 38.5, 42, and 48.5 mW/cm^2 at a frequency of 5.62 GHz. These values were arrived at by positioning the conditioning box at various axial distances from the horn and by utilizing the 0.5 and 2 µs pulse durations. At 1.28 GHz the animals were exposed to 0 (sham), ≤1, 5.5, 9.5, 10, and 15 mW/cm^2 by positioning the box at various axial distances from the horn. The power density of ≤1 mW/cm^2 was arrived at by placing a sheet of microwave absorber between the horn and the conditioning box. During a session the rats were exposed for 40 min and immediately removed when the session terminated. Normally, sham exposures preceded and followed irradiation sessions by one day. Prior to irradiation sessions response rates were allowed to return to between-session stability.

Dosimetric measurements were made with a water (normal saline) model exposed at different distances from horn. The container for the water model, shown in Figure 3, consisted of symetric cavities carved into blocks of Styrofoam. When the blocks of Styrofoam were bound together, the resulting cavity was shaped like a standing rat, had a volume of 385 ml, and could be filled with saline or muscle-simulating material. It was exposed to the vertically polarized radiation in the same orientation as the working rat. In this posture the cervical/thoracic region was nearly horizontal and the lumbo/sacral region was nearly vertical. Temperature changes in exposed saline were measured and the SAR was calculated using the heating-curve technique (1). SAR was also determined for the case in which the cavity was filled with a muscle-simulating material. A four-lead high resistance thermistor (Vitek, Inc., Boulder, CO) was used to obtain the temperature measurements. For the muscle-simulating material, in which the heat could not be readily homogenized by convection, temperature measurements were made at twelve different locations.

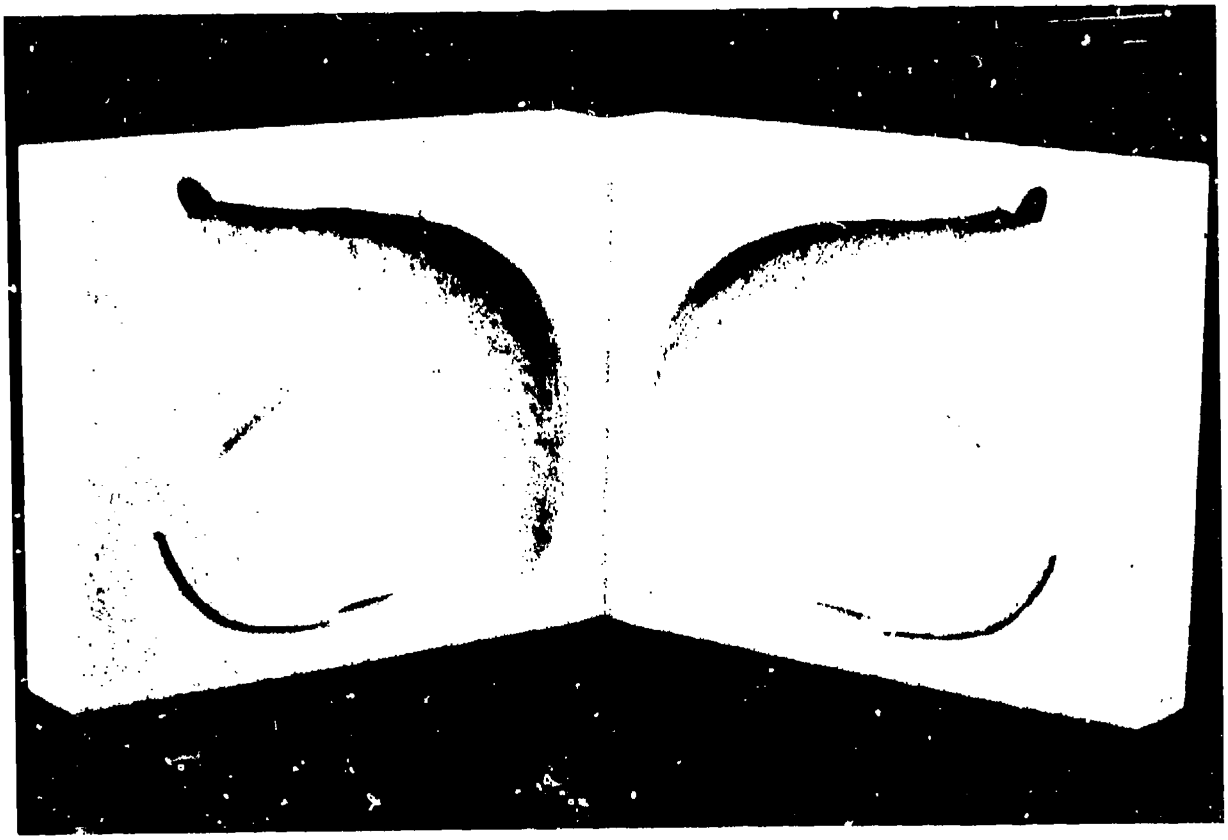

Figure 3. A Styrofoam block containing the rat-shaped cavity used for calorimetric measurements. This cavity was filled with saline or muscle-simulating material and thermistors inserted from the top or back.

RESULTS

DOSIMETRY

The averaged specific absorption rate (SAR), calculated from temperature measurements on the water model, and normalized per unit of incident power density, was 0.25 ± 0.01 (W/kg)/ (mW/cm^2) (mean ± S.D., n = 7) at 1.28 GHz irradiation and 0.19 ± 0.03 (W/kg)/ mW/cm^2) (n = 25) at 5.62 GHz irradiation. These values compare favorably with those calculated for prolate spheroidal models of rats at E and H polarizations (6, p 95).

The localized SAR as measured at the twelve different locations in the muscle-simulating material is shown in Figure 4 along with a diagrammatic representation of the measurement locations in the rat model. The rat model was irradiated with the direction of propagation coming from its right-hand side. The left side of the abscissa in each graph of Figure 4 is nearest to the source of irradiation. The figure illustrates that most of the energy absorbed at 5.62 GHz was in the front surface of the model whereas at 1.28 GHz more energy was absorbed near the rear surface in the head and hip areas. The largest energy distribution differences between exposures at these two frequencies were also in the head and hip areas, and these differences were most pronounced in the model's head.

BEHAVIOR

The response rate on the observing lever (right lever) was consistently disrupted in all eight subjects at 15 mW/cm^2 during exposure to 1.28 GHz microwaves. Typically, the disruption was seen in an overall reduced response rate, long pauses unrelated to food pellet delivery, and in many animals a complete cessation of responding after 15 to 20 minutes of exposure. Similar effects were observed in seven of the rats when exposed to 5.62 GHz microwaves at power densities of 26 mW/cm^2 or greater. To consistently affect the behavior of all eight subjects at this higher frequency a power density of 38.5 mW/cm^2 was necessary. The averages of observing-response rates at the two frequencies and various power densities are illustrated in Figure 5 as ratios of exposed to sham conditions. The points represent means and the bars show one standard error of the mean on each side of the mean. The line at 1.0 indicates that irradiated and sham levels of responding are the same. Figure 5 demonstrates that average observing-response rates during exposure sessions were substantially different from sham sessions beginning at 10 mW/cm^2 in the case of 1.28 GHz and at 26 mW/cm^2 in the case of 5.62 GHz. In both cases responding tended to be increasingly depressed with increased power density.

At both frequencies individual differences existed in an animal's susceptibility to the microwaves. For example, at 1.28 GHz seven of eight rats decreased observing-response rates when exposed to a 10 mW/cm^2 level, yet only one rat was undeniably affected at 9.5 mW/cm^2. Three rats exposed to the lower frequency showed small observing-response rate decreases when first irradiated at 5.5 mW/cm^2, but these decreases did not appear when later irradiated at the same power density. Similar idiosyncratic effects were observed at 5.62 GHz exposures. At the higher frequency one rat was

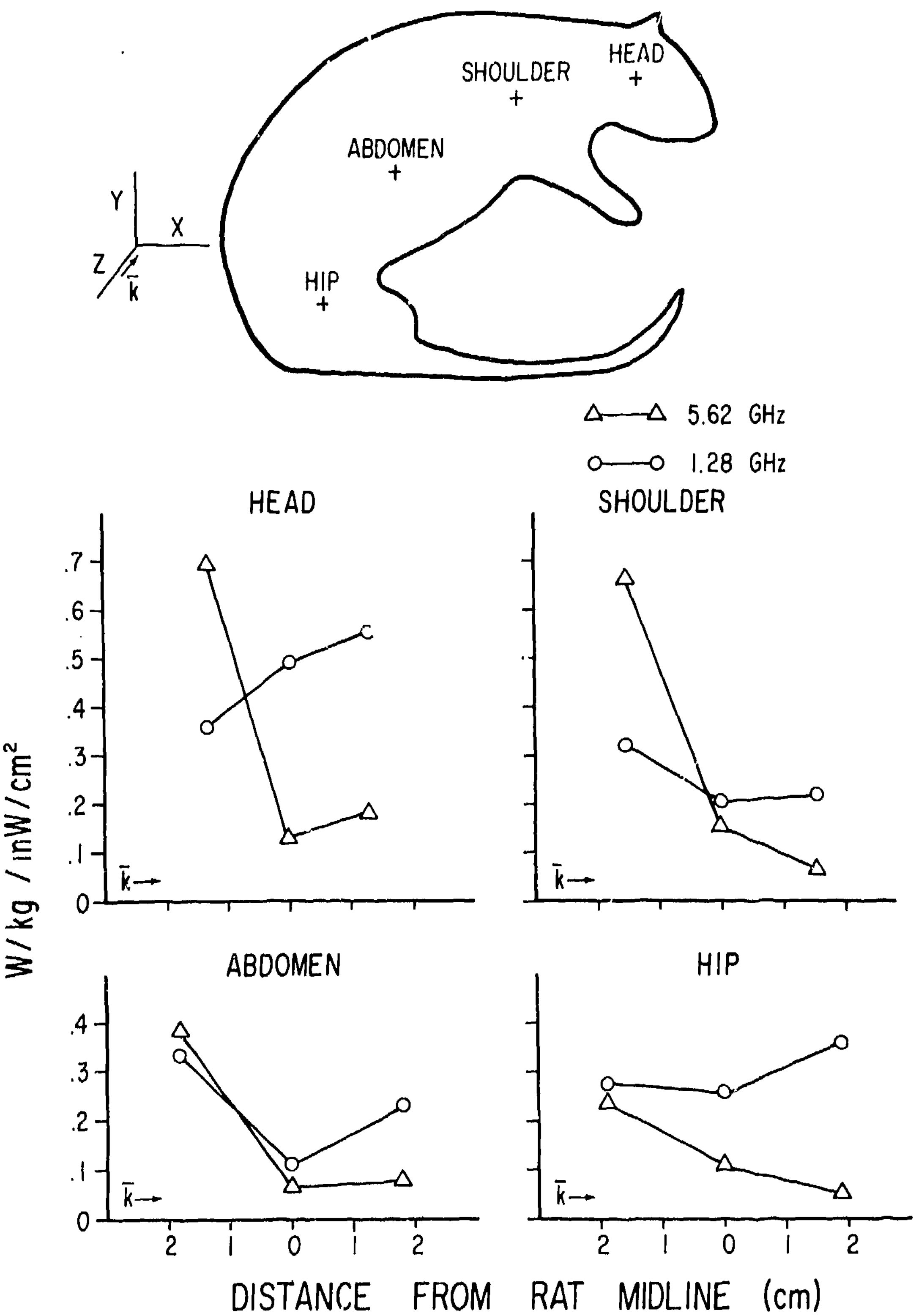

Figure 4. Outline of the rat model showing locations of the temperature measurements. The graphs present the normalized SAR (ordinate) at three axial distances (abscissa) in each location for irradiation at 1.28 GHz (circles) and at 5.62 GHz (triangles).

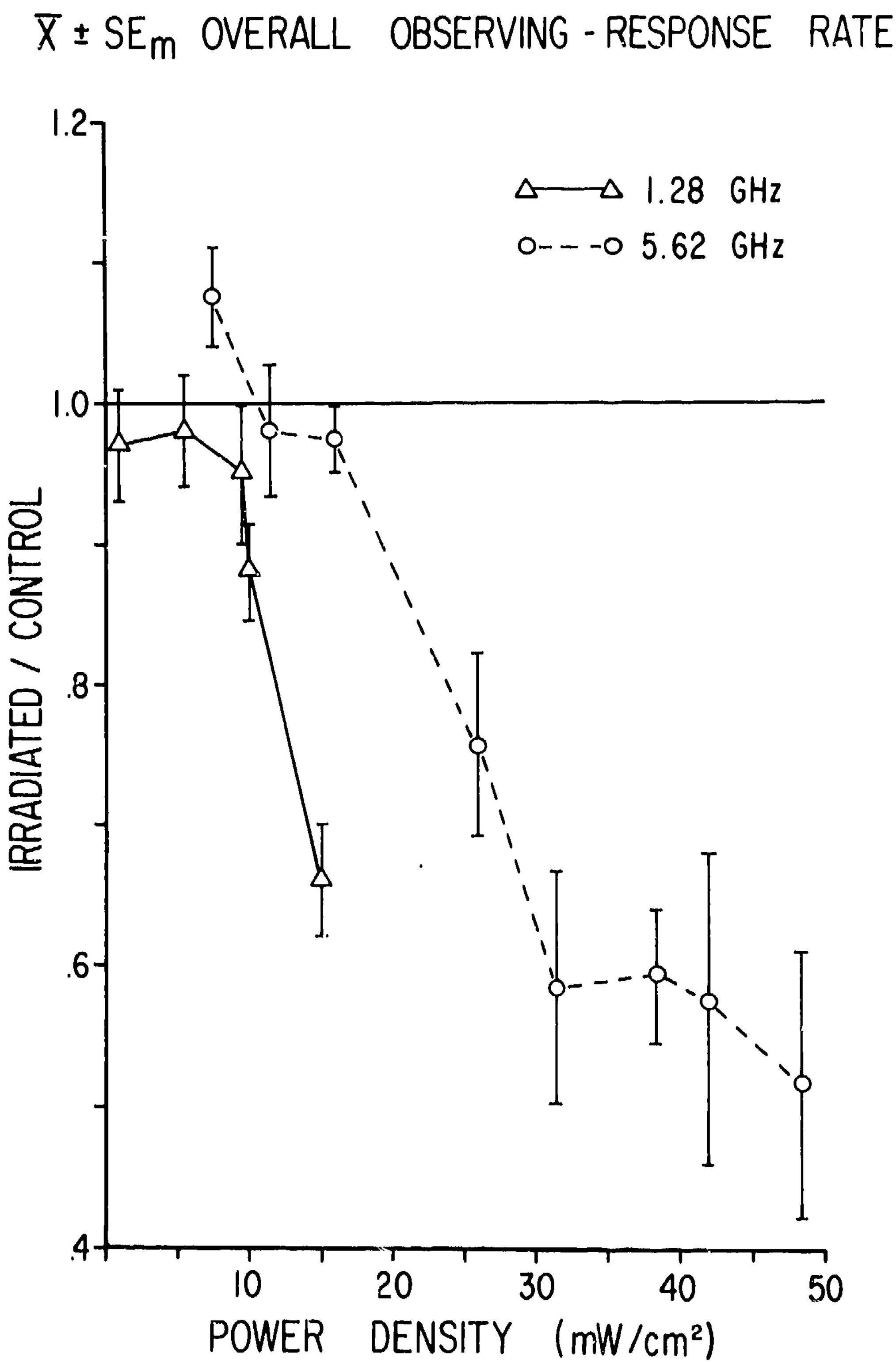

Figure 5. Right-lever (observing) response rate plotted as a ratio of irradiated session means to sham (control) session means including the standard error of these ratios. A ratio of 1.0 (horizontal line) denotes no difference between sham and irradiated conditions.

slightly affected at 16 mW/cm^2 and one was not bothered until exposed to a power density of 38.5 mW/cm^2.

Examples of cumulative records that illustrate the decrease in observing-response rate as a function of duration of exposure are shown in Figures 6, 7, and 8. Figure 6 contains sham and 1.28 GHz exposure records of rat 9, an animal that responded at high rates. The right-hand margin lists the power densities, and the small numbers in the left upper corner of each set of records denote the session number. Each record is of an entire 40-min session. The response pen reset at 280 responses or at the end of a session. The pen was momentarily deflected with each reinforcer and stepped upwards with each observing-response. The pen on the horizontal line below the response record was deflected when the high tone indicating food availability was present. As seen in Figure 6, no obvious effect occurred until a power density of 15 mW/cm^2 was used, and after 20 min the animal completely stopped responding. In addition, at 15 mW/cm^2 this rat frequently failed to make a detection-response to the appropriate tone, thereby foregoing a food pellet as indicated on the horizontal line by the longer pen deflections prior to the cessation of responding.

Figure 7 contains similar records of rat 10 when exposed to sham and 5.62 GHz microwaves. In this figure the lower horizontal line is used only for aligning the response records. The entire series of exposures is not shown; only samples covering most of the series are shown because of space limitations. There is a gradual decrease in responding with exposure to 26 mW/cm^2, followed again by a complete cessation of responding after about 20 min of exposure.

Some of the animals habituated to repeated microwave exposure as shown in Figure 8 for rat 7. This figure contains consecutive sham and exposure cumulative records obtained during exposure to 15 mW/cm^2 of 1.28 GHz irradiation. At the first exposure, session 23, a gradual decrement in rate was followed by a complete cessation of responding within 15 min. After a recovery day the exposure was repeated and responding was less disrupted. Two intervening sham sessions occurred, and the third exposure was even less disruptive at session 28.

Responding incorrectly on the left lever was affected basically in the same manner as observing-responses at both microwave frequencies. These responses could be considered false detections (left-lever responses in the absence of the food-availability tone), and their frequency and that of correct detections decreased with increases in power density, as shown in Figure 9. This decrease was substantial at levels of 10 mW/cm^2 and above during exposure to 1.28 GHz microwaves and at levels of 26 mW/cm^2 and above during exposure to 5.62 GHz microwaves. When analyzed as a function of total observing-responses, there was actually an increase in the mean proportion of false detections as power density increased even though the absolute number of false detections decreased. The extent of the proportional increase in false detections is seen in Figure 10, which shows the means and standard errors of the means at the two frequencies as a function of power density. Although these incorrect responses only increased slightly at 1.28 GHz, the increase at 5.62 GHz was well defined. The correlation coefficient

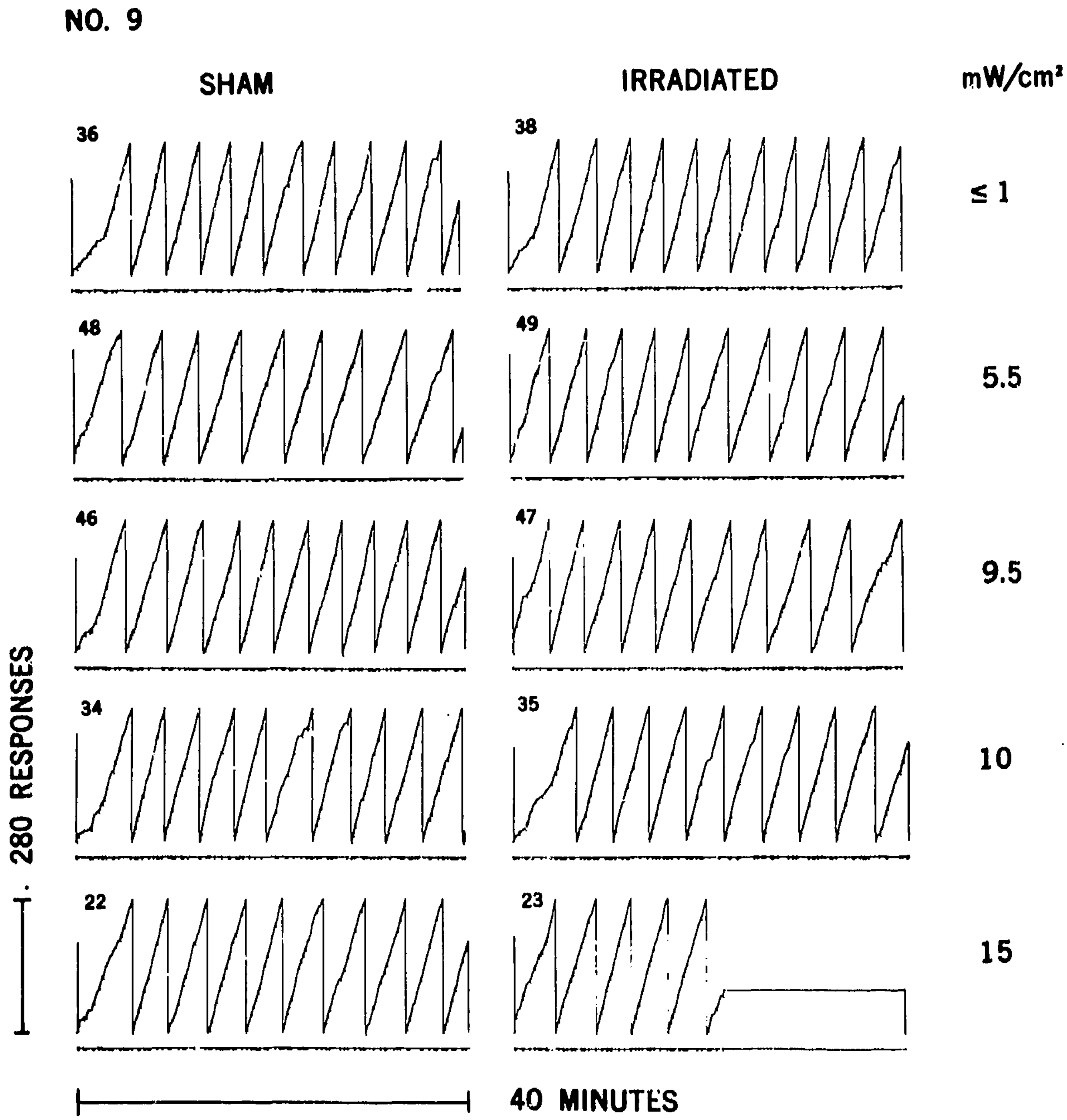

Figure 6. Sham and 1.28 GHz exposure cumulative records of observing-responses for rat 9. Power densities are indicated at the right of each row of records. The smaller number at the left of each session's recording is the session number. Responses are shown on the left and time is indicated at the bottom.

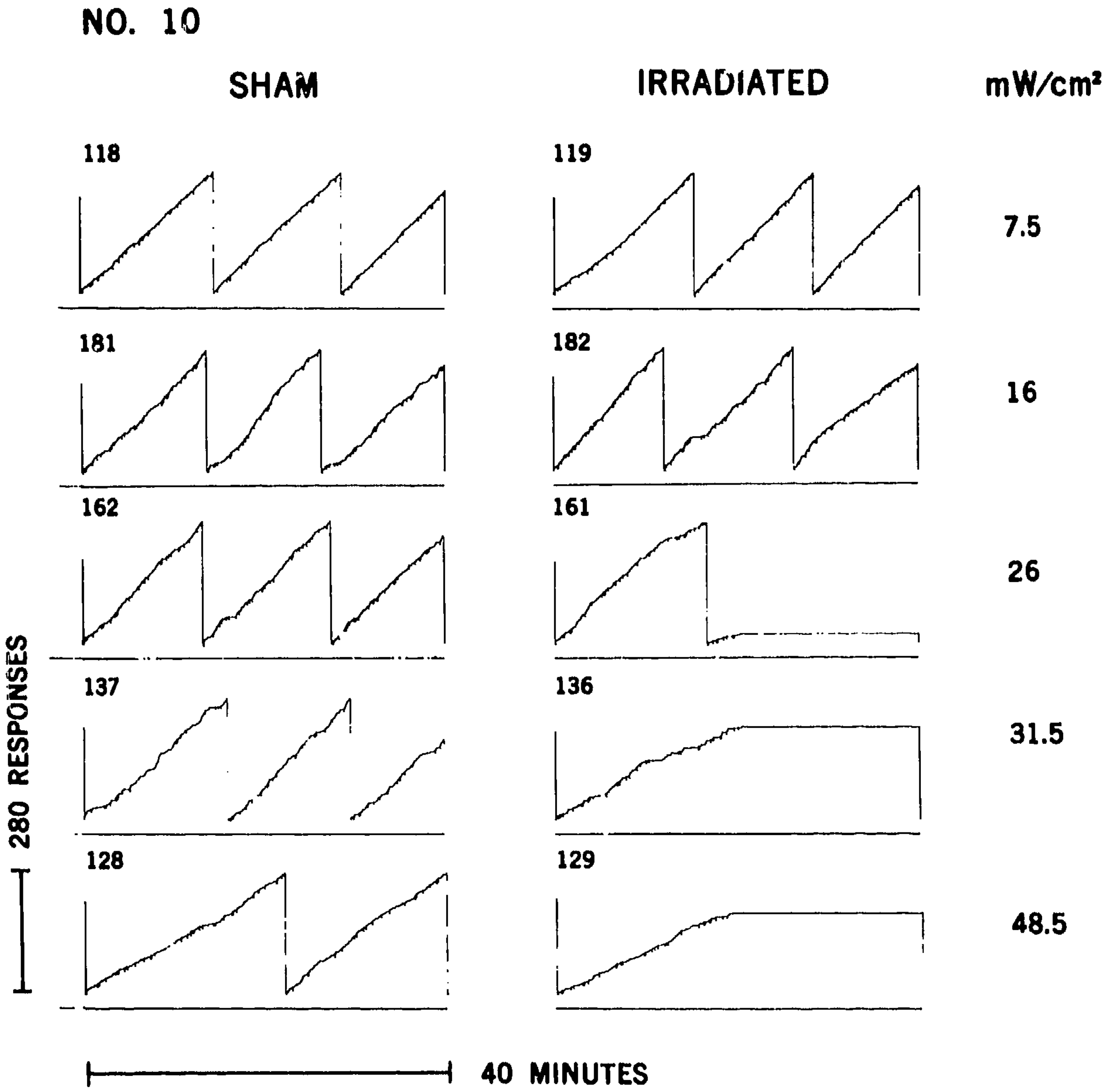

Figure 7. Cumulative observing-response records of rat 10 when exposed to sham and 5.62 GHz conditions. Power densities are shown on the right and session numbers are in the upper left corner of each recording.

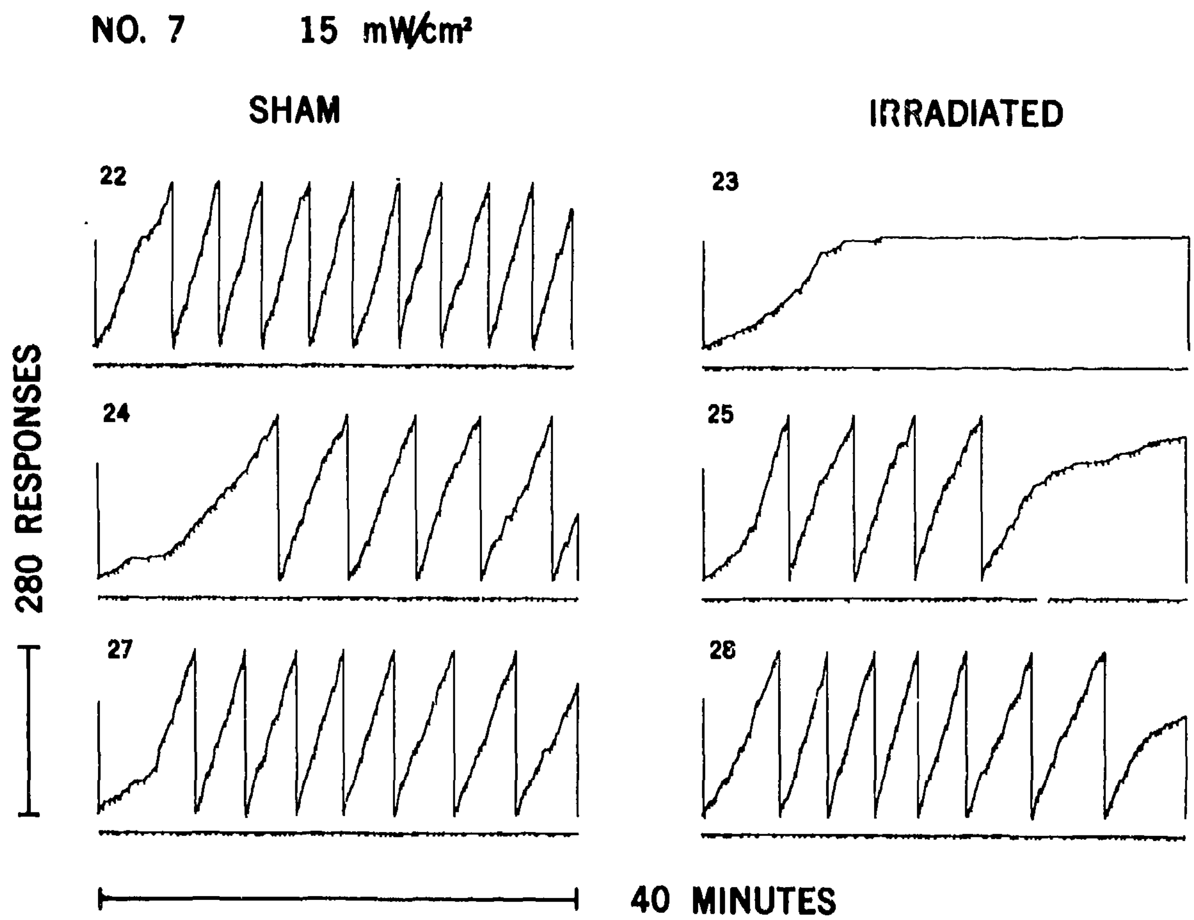

Figure 8. Cumulative observing-response records of rat 7 showing consecutive exposures to sham and 15 mW/cm^2 power densities at 1.28 GHz. The numbers at the upper left of each record are session numbers.

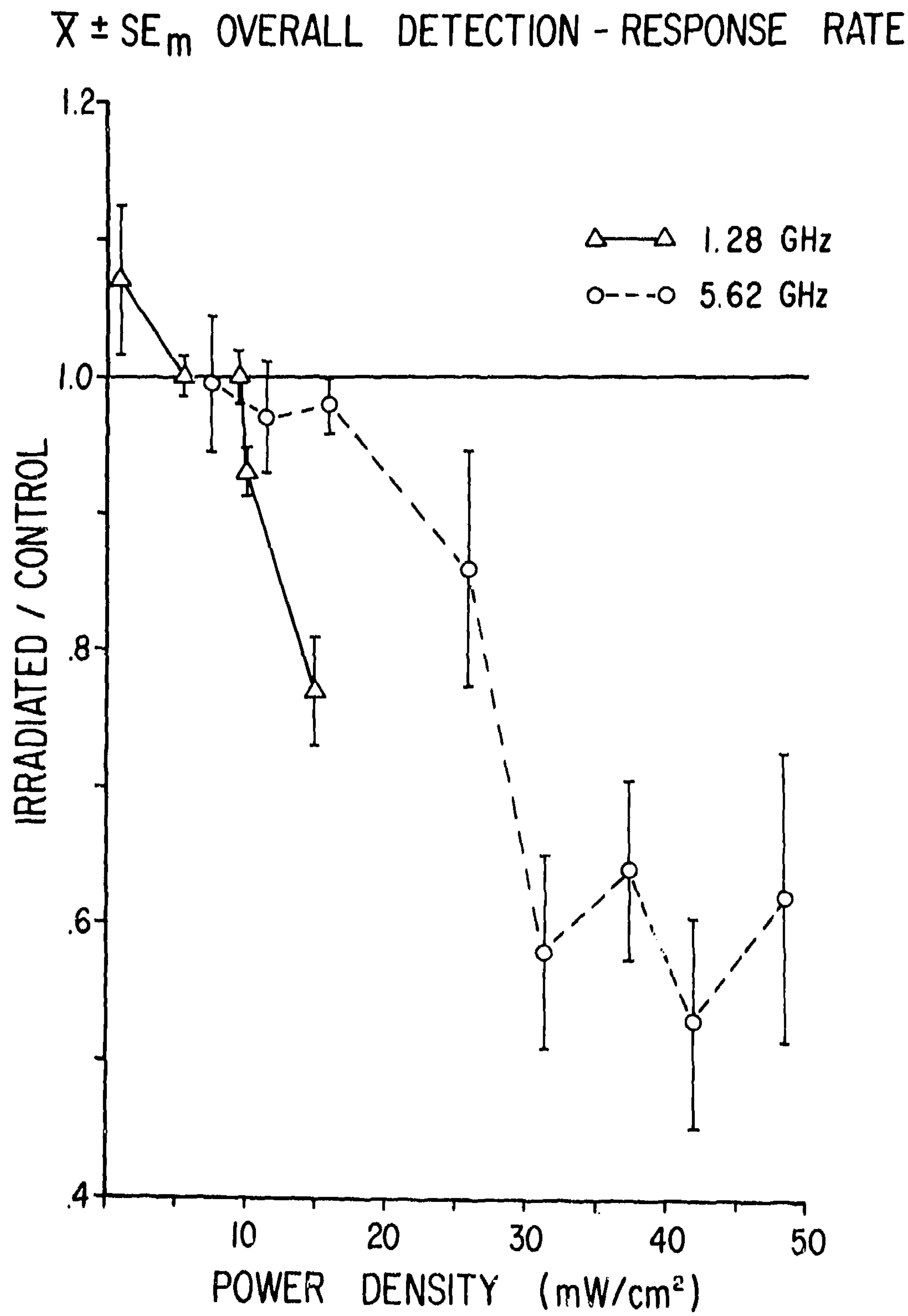

Figure 9. Detection (left lever) response rate shown as a ratio of irradiated session means to sham session means. Each point represents the data from 8 rats.

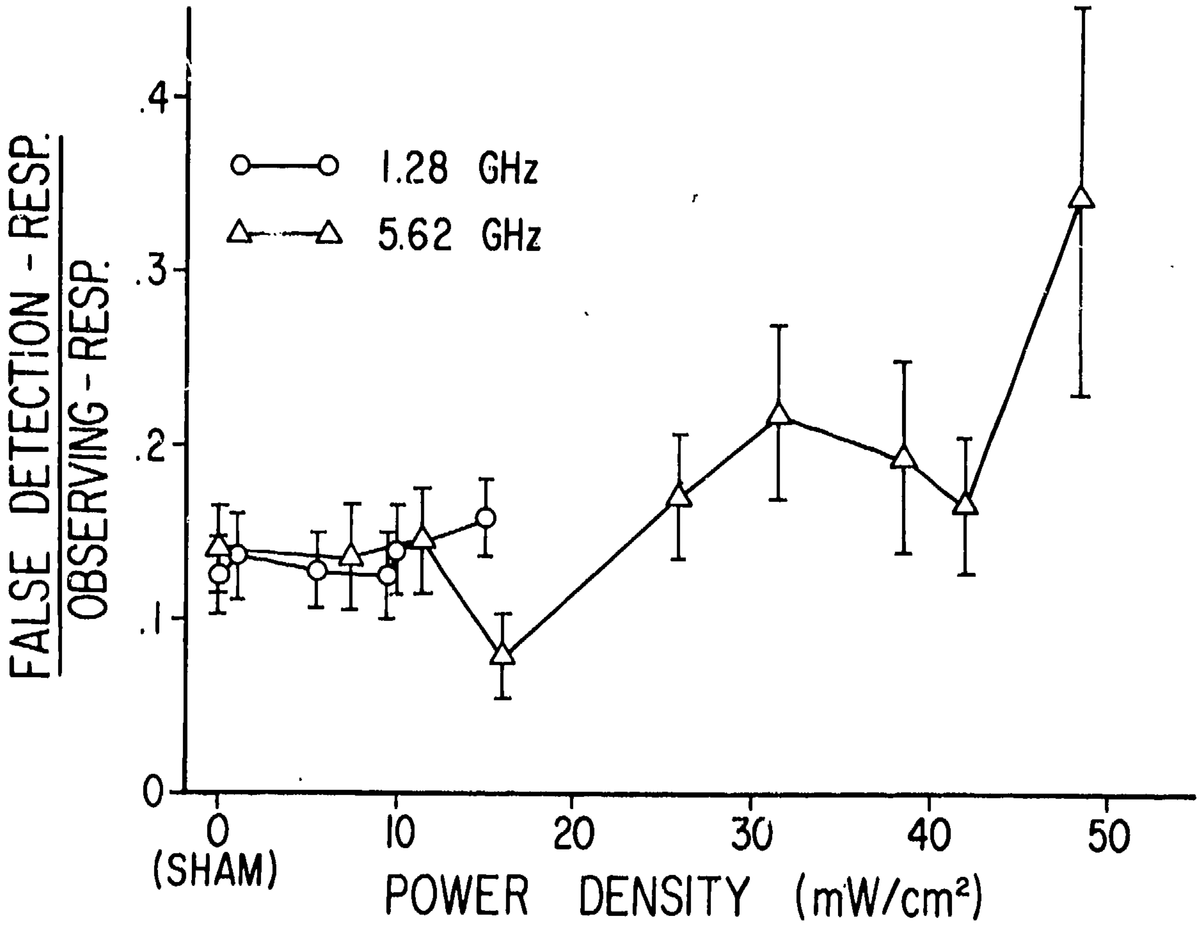

Figure 10. The ratio of false detection-responses to observing-responses shown as a function of power density at the two microwave frequencies.

between power density and false detection-responses was +.61 at 1.28 GHz (not significant at $p < .05$, $df = 4$) and +.72 at 5.62 GHz (significant at $p < .05$, $df = 7$). It must be noted that these increases are relative. The total detection-responses decreased with power density increases as did all responses; it is just that the relative number of false detections increased with increases in power density.

Another effect of the microwaves was seen on the pause time following a reinforced detection-response. This time period increased as power density increased; the result is shown in Figure 11. Like many other measures the increase was not consistently seen until power densities reached 10 mW/cm^2 at 1.28 GHz (a small, but reliable difference) and 26 mW/cm^2 at 5.62 GHz. Nevertheless, in terms of averages, there was an increase in the post-reinforcement-pause time even at 16 mW/cm^2 at 5.62 GHz irradiation.

Neither the latency to make a detection-response, a measure of reaction time traditionally used as an indication of vigilance decrement, nor the probability of detection-responses showed consistent between-subject effects of microwave exposure. In those rats who failed to make detection-responses in the presence of the appropriate signal, the decrease in detection-response probability occurred near the end of exposure sessions. No overt physiological effects of hyperthermia, including wetting of the fur with urine or saliva, were observed in the rats at either microwave frequency.

DISCUSSION

Behavior is a reflection of many physiological processes in an animal and as such includes not only the effects of an environmental change but also the animal's ability to homeostatically compensate for disruptive consequences of environmental changes. Hence, it is not surprising that the rats in the present study showed no consistent behavioral changes at power densities below 10 mW/cm^2 at either microwave frequency used. These animals were food deprived and thus were occupied on a task that not only produced food but also required relatively undivided attention to successfully operate. The fact that most of the subjects showed behavioral disruptions at 10 mW/cm^2 when exposed to 1.28 GHz and showed no behavioral change until exposed to 26 mW/cm^2 at 5.62 GHz is surprising. The averaged SAR (4.9 W/kg) at the 5.62 GHz disrupting level concurs with previous results at 2.45 GHz, but the averaged SAR (2.5 W/kg) at the disruption level of 1.28 GHz is much lower. There are several possible explanations for these differences; the primary one is founded on the unique differences in energy distribution at the two frequencies. Although a higher total SAR was observed at 5.62 GHz, most of the energy was deposited in the outer 5 to 10 mm of the right side of the working rat; whereas at 1.28 GHz a concentration of energy deposition occurred throughout the rat and especially in its head.

At 5.62 GHz the average SAR (4.9 W/kg) corresponding to initial behavioral disruption in the present study agrees with findings in several other studies, although these other studies exposed rats to 2.45 GHz CW irradiation. Some of the similarities are remarkable. Lotz and Michaelson (12) discovered that the threshold for adrenal-axis stimulation corresponded to an SAR of 4.8 W/kg, and de Lorge (4) found the threshold for disruption of rhesus monkeys on a vigilance task to be approximately 4.7 W/kg [according to calculations

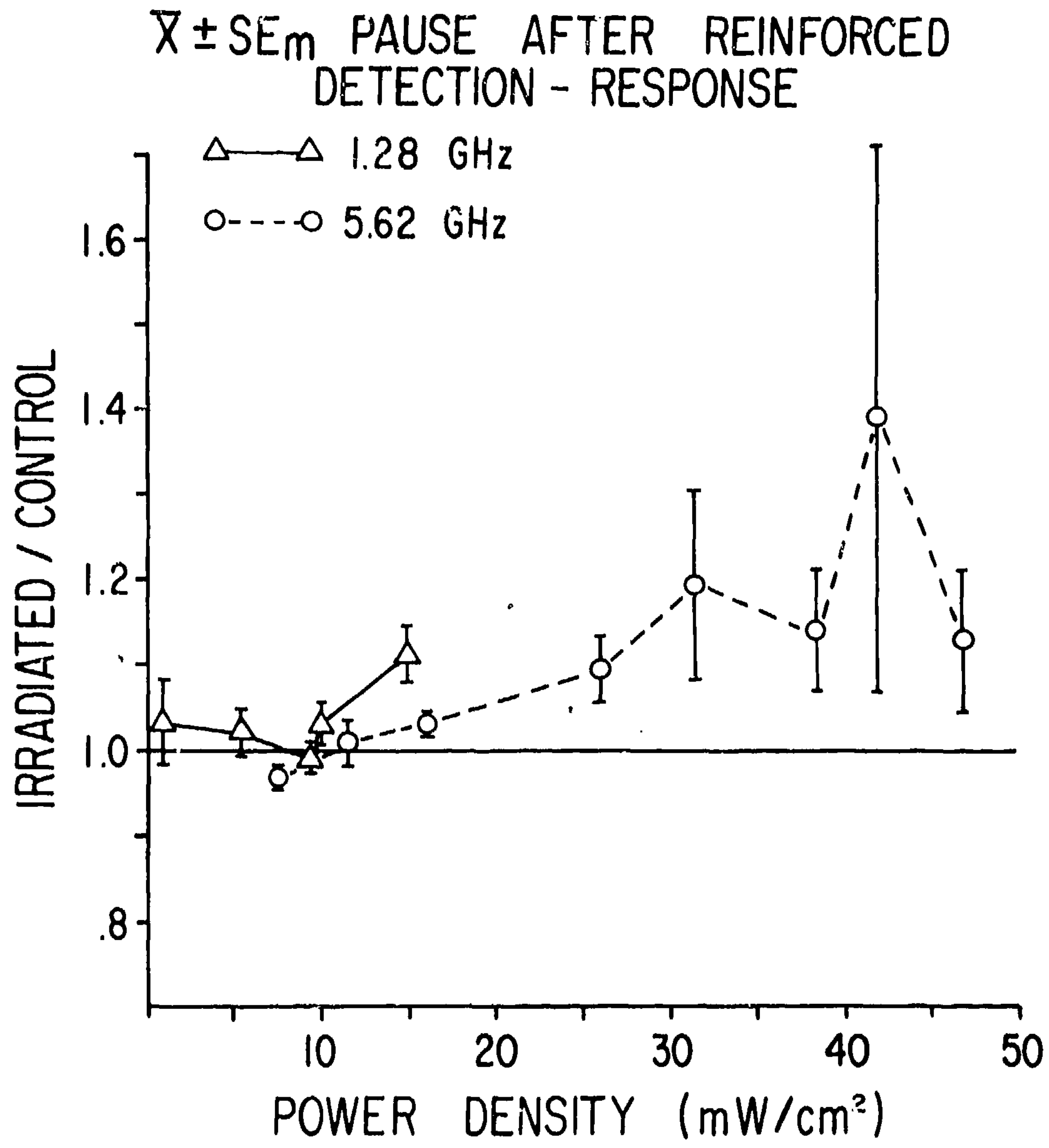

Figure 11. Post-reinforcement pause as a function of power density and microwave frequency. The pause is shown as a ratio of means during irradiation sessions to sham session means.

based on Durney et al. (6)]. Another study by de Lorge (5), with squirrel monkeys on the same task, resulted in finding a threshold at 2.5 W/kg, calculated for K-polarized incident intensity of 45 mW/cm^2. The anomalously low squirrel monkey SAR at this power density was probably due to the bending forward of the monkey in its restraint chair, thereby orienting in more of an E polarization than a K polarization. According to Durney et al. (6), our sitting squirrel monkey at E polarization would have an SAR of 4.5 W/kg. Finally, another study in our laboratory (14) found operant behavior in rats to be disrupted at 28 mW/cm^2 at 2.45 GHz. This power density corresponds well with that in the Lotz and Michaelson study (30 mW/cm^2) which was said to produce an SAR of 4.8 W/kg. In all of these 2.45 GHz studies the average rectal temperature change at the point of behavioral disruption was 1° C, or more, above sham exposure temperatures.

The averaged SAR (2.5 W/kg for 7 of 8 subjects) corresponding to behavioral disruption when the rats were irradiated with 1.28 GHz microwaves differs considerably from reported SARs in similar studies. In fact, two studies with rats found behavioral changes related to SARs of 8.4 and 9 W/kg (9, 11) although different frequencies were used, 918 and 2450 MHz, respectively, as were different exposure conditions, near and far field. The present authors are not familiar with any rat experiments using 1.28 GHz or L band irradiation wherein rectal temperature was also obtained along with behavioral changes.

The primary effect of microwave irradiation, a decrease in response rate, is a typical finding in similar studies [see for example (10)]. The interpretation of this effect, however, has differed considerably. The present authors emphasize that the decrease in observing-response rate is a form of disruption of ongoing behavior and not necessarily a symptom of the perturbation of more covert events; i.e., internal "timing" mechanisms. Traditionally when physical agents interfere with free-operant behavior, the direction of interference is a function of the reinforcement schedule. When high rates of responding are generated by a schedule, lower rates occur with the introduction of physical agents. When low rates of responding are generated by a reinforcement schedule, disruption is typically seen by the occurrence of higher rates [see for example (16)]. Exceptions do occur, but they are rare where the reinforcement schedules normally generate constant response rates.

Evidence of something other than a simple reduction of response rate is seen in the positive correlations between power density and incorrect left-lever responses (false detections). Here, while both left- and right-lever response rates showed decreases, the relative frequency of false detections increased. It was expected that the relationship would remain constant because of the chained nature of detection-responses and food signals. A similar, but less defined result was obtained when squirrel monkeys, working the same task with visual signals (5), were exposed to 2.45 GHz microwaves (120 Hz, 100 percent modulated sine wave). The effect, then, is probably not caused by a confusion of the tones produced by the microwave auditory effect (7) obtained with pulsed radiation. In both the present experiment and the previous one with squirrel monkeys this relative increase in false detections was seen only at the higher power densities; i.e., those power densities that had an obvious effect on the observing-response rate.

CONCLUSIONS

The behavioral disruption produced by electromagnetic radiation in the present study was almost certainly related to the thermal consequences of such radiation, either extensive surface heating or "hot spots." No evidence for the ephemeral "non-thermal" effects of microwaves was obtained. The absorbed energy measurements on models illustrate that even though less average energy may be deposited in the rat at 1.28 GHz, more heat is produced in other than surface areas. This distribution of heat obviously was more disruptive of behavior than the distribution of heat produced at 5.62 GHz although a higher whole-body SAR was evident at the latter frequency when behavior was disrupted.

No evidence of cumulative effects of repeated exposure to microwaves was observed in this study. On the contrary, it was found that repeated exposures allowed the animals to be less perturbed by the irradiation. This observation agrees with similar results wherein 2.45 GHz microwaves were used in rats and monkeys (4, 5, 14). Because body temperatures were not obtained in the present study, conclusions regarding temperature change and temperature adaptation cannot be drawn.

Finally, the present study along with the experiment by Sanza and de Lorge (14) shows an interesting consistency when used with the curves of average SAR produced by Durney et al. (6) for prolate spheroidal models of rats. That is, at 2.45 GHz and higher frequencies the average SAR for rats aligned with E polarization is relatively constant, whereas, at 1.28 GHz more energy is deposited in the rat for the same amount of incident power density. Hence, at 1.28 GHz less incident power density should produce the same amount of behavioral disruption based on the concept of an SAR threshold.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

14

1. REPORT NUMBER: NAMRL—1264

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

6

4. TITLE (and Subtitle): AN EXPERIMENTAL ANALYSIS OF AN OBSERVING-RESPONSE IN RATS EXPOSED TO 1.28 AND 5.62 GHz MICROWAVE IRRADIATION,

5. TYPE OF REPORT & PERIOD COVERED

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)

10

John O./de Lorge [redacted] Clayton S./Ezell

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Aerospace Medical Research Laboratory
Naval Air Station
Pensacola, Florida 32508

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS

17

MF58 524 Ø15 0037

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Medical Research and Development Command
National Naval Medical Center
Bethesda, MD 20014

11

12. REPORT DATE: 5 Nov[redacted]79

13. NUMBER OF PAGES: 23

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

12 26

15. SECURITY CLASS. (of this report)

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

16 F58524

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Operant behavior, Microwaves, Vigilance, Rats

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Naval communications and weapons systems use a variety of microwave producing devices. Frequently fleet personnel may be exposed to the radio-frequency irradiation emanating from such devices. Current scientific reports indicate that biological changes can be produced by nonionizing electromagnetic irradiation and that complex behavioral effects are predominant among these changes.

Few studies of the biological effects of microwave irradiation have

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S/N 0102-014-6601

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4C6061

20. ABSTRACT (Continued)

investigated complex behavior in non-human organisms. One human behavior easily simulated in other animals is monitoring performance, otherwise known as observing-behavior or performance on a vigilance task. This task requires an animal to respond, thereby producing one or more stimuli. When the stimuli change, the animal has to report the change to obtain a reinforcer. In the present study the effects of two different microwave frequencies (1.28 and 5.62 GHz) on observing-behavior in rats were investigated.

At 1.28 GHz the observing-response rate was consistently affected at a power density of 15 mW/cm^2 in all eight rats while at 5.62 GHz the observing-response rate was not consistently affected until the power density approximated 26 mW/cm^2. Measures of the averaged specific absorption rate (SAR) in a rat model of simulated muscle tissue illustrated a distribution difference at the two different frequencies. The SAR distribution within the model's head at 1.28 GHz was the inverse of the distribution in the head at 5.62 GHz. It was concluded that the rat's behavior was more easily disrupted at 1.28 GHz than at 5.62 GHz because of the deeper penetration of energy at 1.28 GHz and differences in energy distribution at the two frequencies.